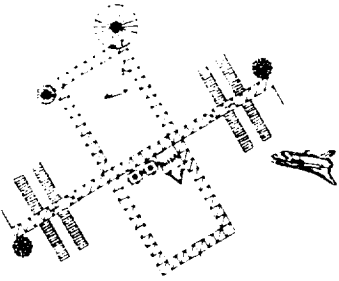


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THE  
SPACE STATION  
TETHERED ELEVATOR SYSTEM

UNIVERSITY OF CENTRAL FLORIDA  
FINAL REPORT

Submitted to:

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

and

THE UNIVERSITIES SPACE RESEARCH ASSOCIATION

(NARA-CR-134061) THE SPACE STATION TETHERED  
ELEVATOR SYSTEM (University of Central  
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## Foreword

The SPACE STATION TETHERED ELEVATOR is one of a continuing series of Senior design studies carried out by students in Mechanical and Aerospace Engineering 4505, "Engineering Design". This course caters to a variety of design interests of aerospace and mechanical engineering students at the University of Central Florida. The primary output of the course consists of (1) an oral design review (2) a scale model of the design, and (3) the final report.

The goal of this year's project, conceived in discussions with the Space Station Office at Kennedy Space Center, is to produce an optimized conceptual engineering design of a tethered elevator for the International Space Station. Emphasis is placed on the elevator's structural configuration and three major subsystem designs. Elevator robotics are designed to aid in elevator operations and tethered experimentation. A drive mechanism to propel the elevator along the tether, and a self-sufficient power generation and transmission system complete the three subsystem designs.

The tethered elevator has several promising features. It can serve as a remote laboratory platform, a transport system, or a service vehicle. These capabilities expand the operating environments provided by the space station.

The SPACE STATION TETHERED ELEVATOR team consisted of 31 Engineering students. Michael H. Haddock served as graduate teaching assistant during both fall and spring semesters. Mike's efforts coordinating and guiding the many interfaces of the tethered elevator design were invaluable. Thirteen undergraduate students participated during the fall semester, seventeen undergraduate students participated during the spring semester, and one fall semester student performed an independent study in support of the design during the spring semester. Ken Hosterman, the incoming teaching assistant, had the major task of integrating the inputs from the four design groups into this final report. Assisting the documentation effort were Ed Decresie, Peter Miranda, and Russ Hamilton. The scale model was created, designed, and managed by Dan Justin, an independent study student.

We gratefully acknowledge our second year of full support from the National Aeronautics and Space Administration and the Universities Space Research Association in the NASA/USRA Advanced Space Design Program. Special recognition is due Stanley R. Sadin, Director of USRA Strategic Development; Steve Hartman, Program Manager of University Space Programs; and Sherry McGee, University Space Programs, NASA Headquarters, Washington, D.C. At USRA in Houston, TX special recognition is due John Sevier, Director and Carolynne Hopf, Deputy Director, Educational Programs; John Alred, Manager

of Advanced Design Programs; and Barbara Rumbaugh, Senior Project Administrator of Advanced Design Programs. For guidance and help searching out technical documentation we greatly appreciate the efforts of Jane Page, Dorothy Price, Donna Atkins, Ramon Budet, Cristal Woods, and Joann Ratliff of the KSC library. We are especially indebted to C. M. Giesler, Greg Opresko, Jim Aliberti, Dennis Matthews, Jose Alonso, Bruce Larsen, and Dave Springer of Kennedy Space Center, FL, for their technical support and encouragement throughout the academic year.

Professor Loren A. Anderson

May 15, 1989

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## LIST OF ACRONYMS

ADC	- Analog-to-Digital Converter
ADM	- Accurate Displacement Method
ASCII	- American Standard Code for Information Interchange
CCD	- Charged-Coupled Device
CM	- Center of Mass
CPU	- Central Processing Unit
CRC	- Communications Research Centre
DEC	- Digital Equipment Corporation
ED	- Extended Drum
emf	- Electromotive Force
ER	- Extended Rotor
ERM	- Extendable and Retractable Telescopic Mast
ERSD	- Extended Rear Shaft Drum
ERSR	- Extended Rear Shaft Rotor
ETS	- Electrodynamic Tether System
EVA	- Extravehicular Activity
FMI	- Fiber Materials Incorporated
GPHS	- General Purpose Heat Source
HCA	- Hollow Cathode Assembly
IBM	- International Business Machines
IOP	- Input / Output Processor
LBJ	- Lyndon B. Johnson
LEOTAD	- Low Earth Orbiting Tethered Accession Device
MIMCL	- Mirror Image Motion Control Law
MITG	- Modular Isotopic Thermoelectric Generators
NASA	- National Aeronautics and Space Administration
OMS	- Orbital Maneuvering System
OMV	- Orbital Maneuvering Vehicle
PD	- Pulley Drum
PH	- Positive Hold
PMG	- Plasma Motor / Generator
PR	- Pulley Rotor
RTG	- Radioisotopic Thermoelectric Generators
SBIR	- Small Business Innovative Research
SEE	- Standard End Effector
SHARP	- Stationary High-Altitude Relay Platform
SNAP	- Systems for Nuclear Auxiliary Power
SNL	- Sandia National Laboratory
SRMS	- Shuttle Remote Manipulator System
SRV	- Service Removable Units
SS	- Space Station
SSTE	- Space Station Tethered Elevator
TDRSS	- Tracking and Data Relay Satellite System
TECTS	- Tethered Elevator Crawler Transporter System
TERMS	- Tethered Elevator Remote Manipulator System
TSS	- Tethered Satellite System
UAH	- University of Alabama, Huntsville

## LIST OF SYMBOLS

ac	- Alternating Current
atm	- Atmosphere
AU	- Astronomical Unit
Btu	- British Thermal Unit
DegC	- Degrees Celsius
cf	- Cubic Feet
cm	- Centimeter
DC	- Direct Current
DegF	- Degrees Fahrenheit
g	- Gram
GaAs	- Gallium Arsenide
Hg	- Mercury
hr	- Hour
in	- Inch
J	- Joule
K	- Kelvin
kg	- Kilogram
kJ	- Kilojoule
KOH	- Potassium Hydroxide
kW	- Kilowatt
lb	- Pound
LH2	- Liquid Hydrogen
LOX	- Liquid Oxygen
m	- Meter
mm	- Millimeter
mmHg	- Millimeters of Mercury
Nd	- Neodymium
nm	- Nautical Mile
psi	- Pounds per Square Inch
psig	- Pounds per Square Inch Gage
rpm	- Revolutions per Minute
s	- Seconds
Si	- Silicon
W	- Watt
YAG	- Yttrium, Aluminum, Garnet

# FALL PICTURE

DO NOT  
NUMBER  
↓  
10

# SPRING PICTURE

DO NOT  
NUMBER

11



# Space Station Tethered Elevator System

## Project Participants

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# THE SPACE STATION TETHERED ELEVATOR SYSTEM

## EXECUTIVE SUMMARY

The optimized conceptual engineering design of a space station tethered elevator is presented. The elevator is an unmanned mobile structure which operates on a ten kilometer tether spanning the distance between the Space Station and a tethered platform. Elevator capabilities include providing access to residual gravity levels, remote servicing, and transportation to any point along a tether. The report discusses the potential uses, parameters, and evolution of the spacecraft design. Engineering development of the tethered elevator, performed at the University of Central Florida, is the result of work conducted in the following areas:

- \* Structural Configurations
- \* Robotics
- \* Drive Mechanisms
- \* Power Generation and Transmission Systems

The structural configuration of the elevator is presented in Section I. The structure supports, houses, and protects all systems on board the elevator. The elevator configuration evolved as an elongated octagon fitted with a slotted guide vane to facilitate tether insertion. Dynamic control of the elevator is monitored by an internal arrangement of worm gears which interface each drive mechanism. Center of mass management is performed with telescoping struts affixed to payload mounting plates. Standard space shuttle pallets, attached to these plates, support all elevator-based payloads and experiments.

The implementation of robotics on board the elevator is discussed in Section II. Elevator robotics allow for the deployment, retrieval, and manipulation of tethered objects. Robotic manipulators also aid in hooking the elevator on a tether. The system design consists of two diametrically opposed robotic arms. The arms are scaled versions of the Shuttle's Spar Aerospace manipulator and are controlled by a general purpose IBM AP-101 computer.

Critical to the operation of the tethered elevator is the design of its drive mechanisms, discussed in Section III. Two drivers, located internal to the elevator, propel the vehicle along a tether. These modular components consist of endless toothed belts, shunt-wound motors, regenerative power braking, and computer controlled linear actuators. The

drivers are configured with rotating disks to capture and release the tether during elevator mate/demate operations.

The designs of self-sufficient power generation and transmission systems are reviewed in Section IV. Thorough research indicates all components of the elevator will operate under power provided by fuel cells. The fuel cell system will power the vehicle at seven kilowatts continuously and twelve kilowatts maximally. Spherical pressure vessels located interior to the elevator house the power-producing hydrogen and oxygen elements. A set of secondary fuel cells provides redundancy in the unlikely event of a primary system failure. Power storage exists in the form of Nickel-Hydrogen batteries capable of powering the elevator under maximum loads. Coaxial cable is the selected method for transmitting and distributing electrical power produced on board the elevator.

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## INTRODUCTION

- \* Space Station: A New Beginning
- \* The Tethered Elevator Concept
- \* Tether Fundamentals
- \* Designing the Tethered Elevator

## INTRODUCTION

### Space Station: A New Beginning

"The Congress hereby declares that it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind..."[1]

With these words Congress enacted the National Aeronautics and Space Act which created NASA in 1958 and continues to guide its policies today. Following in the same enthusiasm and determination, President Ronald Reagan, in his State of the Union Message on January 5, 1984, directed NASA to "...develop a permanently manned Space Station and to do it within a decade."

This commitment to the future, ripe with intellectual and technical challenge, holds vast opportunities for commercial profit and the preservation of the nation's economic vitality. The Space Station symbolizes America's significant advancements in space and a determination to remain undeterred by the loss of Challenger and her crew.

The practical benefits of the Space Station will be many, serving a diverse range of functions. A few of these functions are anticipated to be:

- \* A laboratory in space, for the development of new technologies and the conduct of science,
- \* A permanent observation post used for the study of Earth sciences, as well as to peer out to the edge of the universe,
- \* A facility where payloads and spacecraft can be maintained and repaired,
- \* A location where vehicles can be deployed to their destinations,
- \* A staging base for future space endeavors.

Much progress has already been made in the development of this program. The road still ahead will be rigorous and demanding. A unique partnership has been established with Canada, Europe, and Japan to provide elements, that together, will make the Space Station a fully functional reality.

The Space Station project symbolizes leadership in space for the United States as a necessary component of civil space policy. Opportunities for private business profits will also improve the national economy. However, the advantages are not just limited to the United States. Because the operation of the Space Station is to be an international effort, it will benefit everyone by allowing mankind to move beyond the confines of Earth as never before possible.

### The Tethered Elevator Concept

For years, America's journey into space has demonstrated the benefits associated with working in the unique environment of microgravity. With the advent of Space Station Freedom, the United States will enter an era marked by a permanent presence in space. Moreover, the Space Station will allow continuous rather than intermittent operations to be conducted in orbit. The Station will open new doors to many new methods of research and experimentation. Furthermore, man will better explore the Earth on which we live and the solar system of which we are a part.

A permanent presence in space will allow a multitude of new and varied technologies to evolve. One of the technologies currently being developed is tether technology. The idea of tethers in space dates back to the mid 1800's. Now, as the idea is reaching technical maturity, tethers in space will be used in innovative ways for many applications. The objective of this report is to present an optimized spacecraft design that will complement the use of tethers in space; namely, the tethered elevator.

The space station tethered elevator has several uses. An elevator can serve as a remote laboratory platform, a transport system, or a service vehicle. This multifunctional capability will allow scientists to tap resources and environments which at the present time are inaccessible. Additionally, an elevator will provide basic elements needed to further explore the operating environments of both the space shuttle and space station.

Use of the elevator as a remote laboratory to access and control the gravity acceleration level is one of the most promising features offered by the system. By precisely positioning the elevator near the center of gravity (CG) on a tether system of fixed length, a minimum gravity acceleration level of  $10E-8$  could be attained.[2] Scientists would then be able to take advantage of residual gravity levels as well as the clean environment provided by a remote laboratory in space.

The elevator can function as an exchange vehicle between the space station and a tethered mass. In this role, the transporter will be used to deliver payloads from the Shuttle to the space station. This allows an orbiter to dock with a tethered mass at some distance from the station, thus saving fuel and increasing payload capacity. The elevator could transport substances such as refuse requiring orbital deboosting.[2] This is accomplished by lowering the elevator along the tether to a predesignated position and then releasing the transported item. Decreasing the tethered mass has the advantage of transferring momentum to the space station and boosting its orbit, with no expenditure of fuel.[3]

Lastly, the potential for the elevator as a remote servicing vehicle exists. If repairs were needed on a tethered mass such as a spacecraft or satellite, the elevator could be deployed to provide assistance. The provision of robotics on board the elevator would enable manipulation of various articles such as mechanical and electrical umbilicals and orbital replacement units (ORU's).

### Tether Fundamentals

The concept of tapping various levels of residual gravity arises from the forces between two masses traveling in different orbits while constrained to move together. These forces are known as gravity-gradient forces and are fundamental to the applications of controlled gravity. The principles behind these forces, though basic, need to be addressed.

Consider Figure 1, which shows two tethered masses, constrained to move together, oriented such that there is a vertical separation between them. Since angular velocity is inversely proportional to orbital radius, an unconstrained upper mass would move at a slower speed than an unconstrained lower mass. Therefore, the tether provides the means by which the masses travel at the same speed (i.e., the tether speeds up the upper mass and slows down the lower mass). As a result, the upper mass experiences a larger centrifugal acceleration, while the lower mass experiences a larger gravitational acceleration. The resultant forces act equal and opposite at the system's center of gravity, giving rise to a balanced tension in the tether. The end masses experience this tension as an induced artificial gravity.

For a tethered system in low Earth orbit, the induced artificial gravity and the tether tension are equivalent to the gravity-gradient force on the system. In short, the gravity-gradient force is the difference between the gravitational and centrifugal forces acting on an end mass,

# TETHER SYSTEM CONFIGURATION

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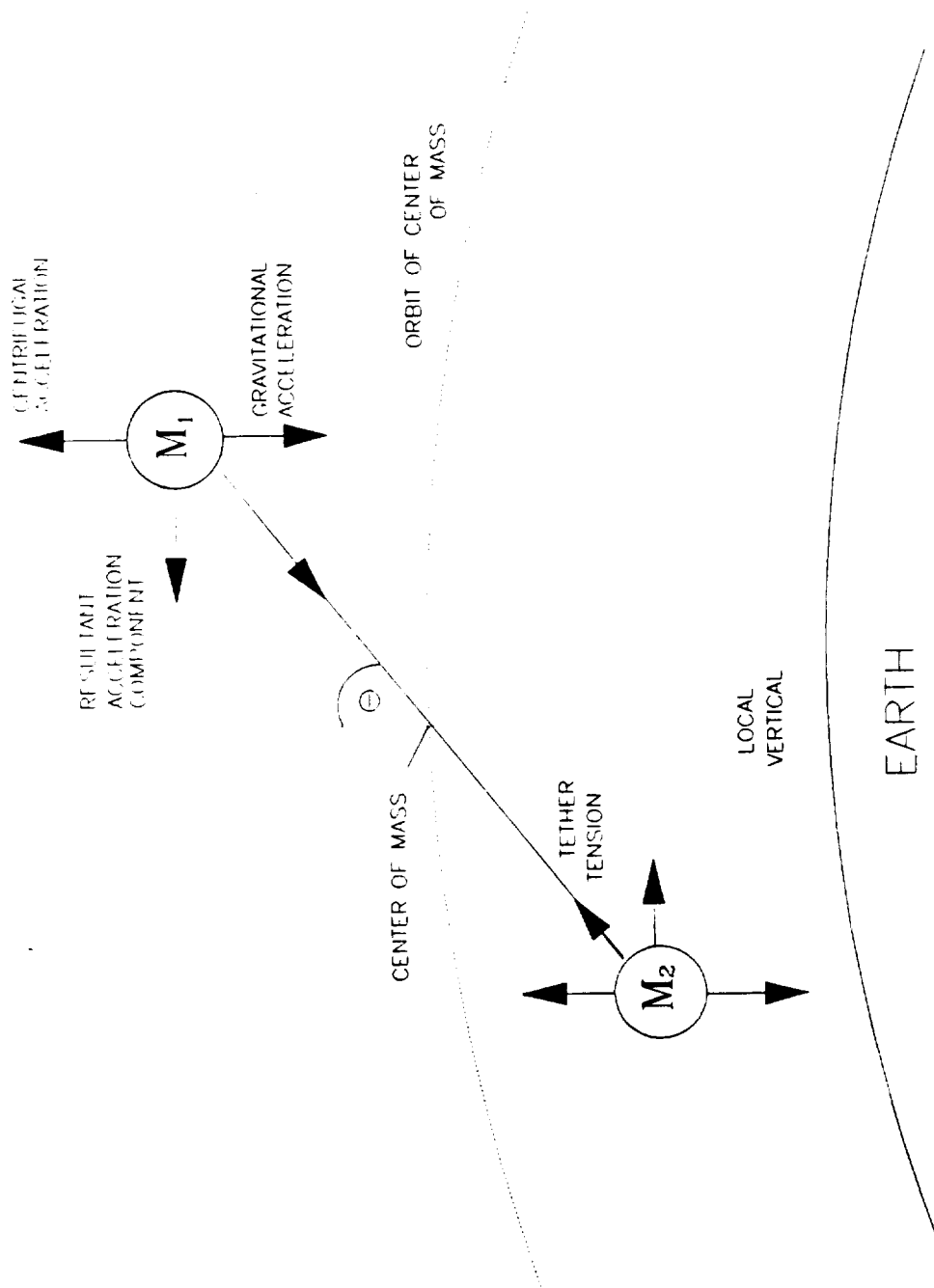


Figure 1.



m, at a distance, l, from the system's center of gravity. A representation of the gradient force is shown in Figure 2. Acting upward above the center of gravity, and downward below it, the gradient force increases as the distance, l, increases, and as the orbital radius of the system decreases. The maximum value of this force occurs at the end masses, with the minimum at the center of gravity. In essence, the center of gravity is the only component of the system in free fall as it orbits the Earth.

An object traversing the tether from the lower mass to the upper mass requires a sufficient drive mechanism to overcome the effect of the downward gradient force. After passing the system's center of gravity, the object would be propelled upward due to the increasing centrifugal force where braking would be required. By traveling in either direction from the center of gravity, an object can be made to experience these varying levels of residual gravity.

The tethered system will remain in a vertical orientation due to the restoring nature of the gradient forces present. Though stable, there are external forces which will cause the system to oscillate about the vertical. These weak, but unavoidable forces include the effects of the Earth's non-spherical shape, drag due to varying atmospheric densities encountered in polar orbits, and solar heating. Conducting tethers must also deal with electrodynamic forces inherent with their operation. The dampening of these oscillations may be accomplished by varying tether length. The greater the tether length, the greater the dampening effect. Applications of thrusters on the end masses or moveable counter-masses on the tether could serve to also dampen the oscillations.

A tethered system can provide numerous applications through the redistribution of the system's angular momentum. The system can neither create nor destroy its angular momentum and can only transfer it from one body to another. Various techniques may be applied to extract this momentum exchange. An example is the boost/deboost technique.

Consider two masses in sufficiently different orbits, connected by a tether. After providing an initial impulse to initiate separation, the upper mass would experience a boost to a higher orbit due to the centrifugal force acting on it. The lower mass would experience a deboost to a lower orbit via the gravitational force acting on it. The potential energy associated with the upper mass would be raised with a subsequent loss in kinetic energy due to the higher orbit and slower angular velocity. The converse would be true for the lower mass.

## GRAVITY-GRADIENT FORCES

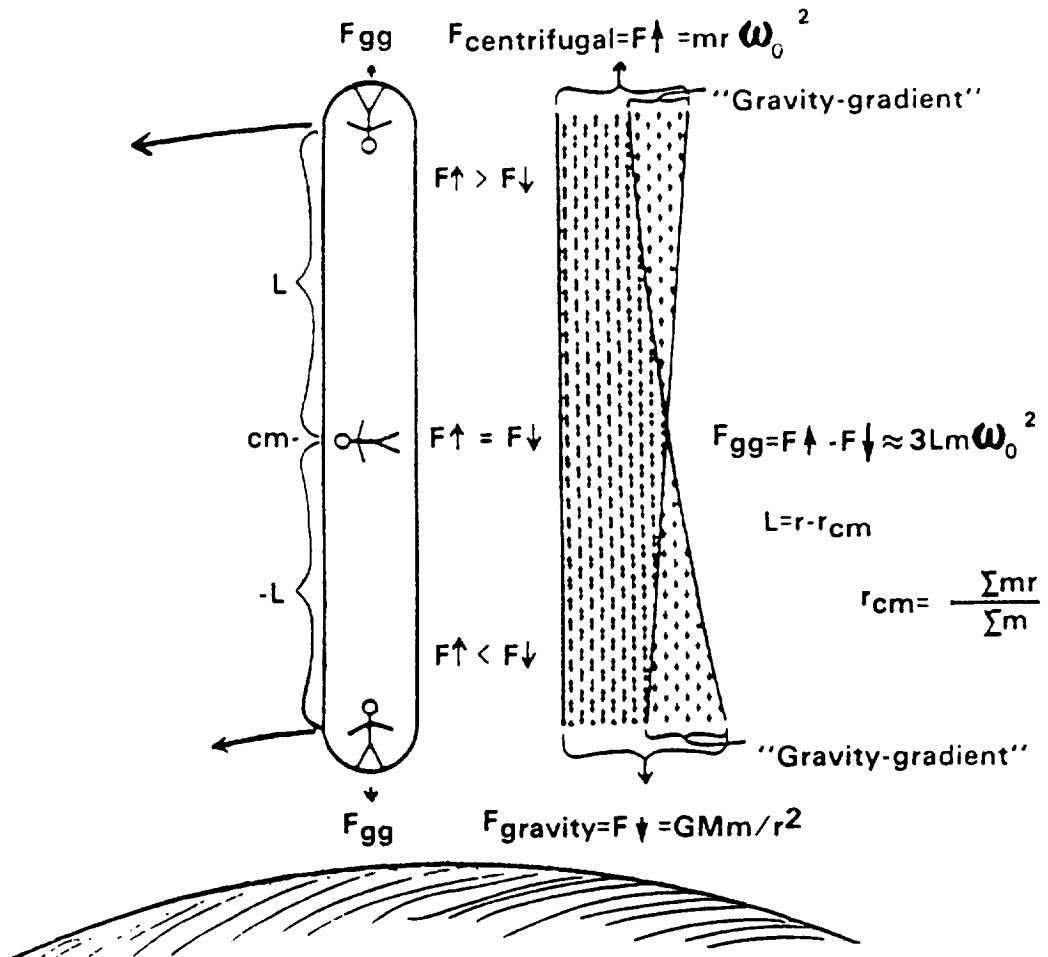


Figure 2.

A way of securing additional boost/deboost to the system can be accomplished by applying a braking force to the lower mass. The effect of this would create a prograde swing in the tether system. Upon severing the tether, the additional velocity seen by the upper mass would translate into added boost. A utilization of this procedure could be applied to the anticipated re-supply missions of the Space Station by the Shuttle. After the re-supply has been completed, the Shuttle would provide a braking force by means of its maneuvering thrusters. After a sufficient swing has been generated, the tether would be severed. The Space Station would be boosted to a higher orbit while the Shuttle would be deboosted back to Earth with minimal expenditure of energy. The fuel not needed for re-entry could be used to orbit heavier payloads by the Shuttle.

### Designing the Tethered Elevator

To best meet the multitude of design objectives for the Tethered Elevator System, four student design teams were assembled each semester. These students met regularly twice a week for a total of eight hours. Two hours were dedicated to Engineering Design lectures, and six hours were devoted to the development of the Tethered Elevator design. During the design process, students performed research at the Kennedy Space Center Library and Documents department. Research was also performed in the University of Central Florida's library. A speaker phone was utilized to obtain technical information and conduct conference calls.

At the outset of the project, each design group was given a "guidelines booklet." This booklet contained all information needed to familiarize the students with the Tethered Elevator project. Subsequent to identifying outlined design tasks, the Engineering Design class embarked on the development of the Tethered Elevator System. (See Figure 3)

The design of the Tethered Elevator System is the product of work performed in the following four phases:

- \* Problem Inquiry
- \* Specifying Goals
- \* Determining Means
- \* Solution Optimization

First, the Problem Inquiry phase was addressed. It stresses the identification of basic design needs, technical issues, and potential problems that may be encountered during the

## *DESIGN APPROACH*

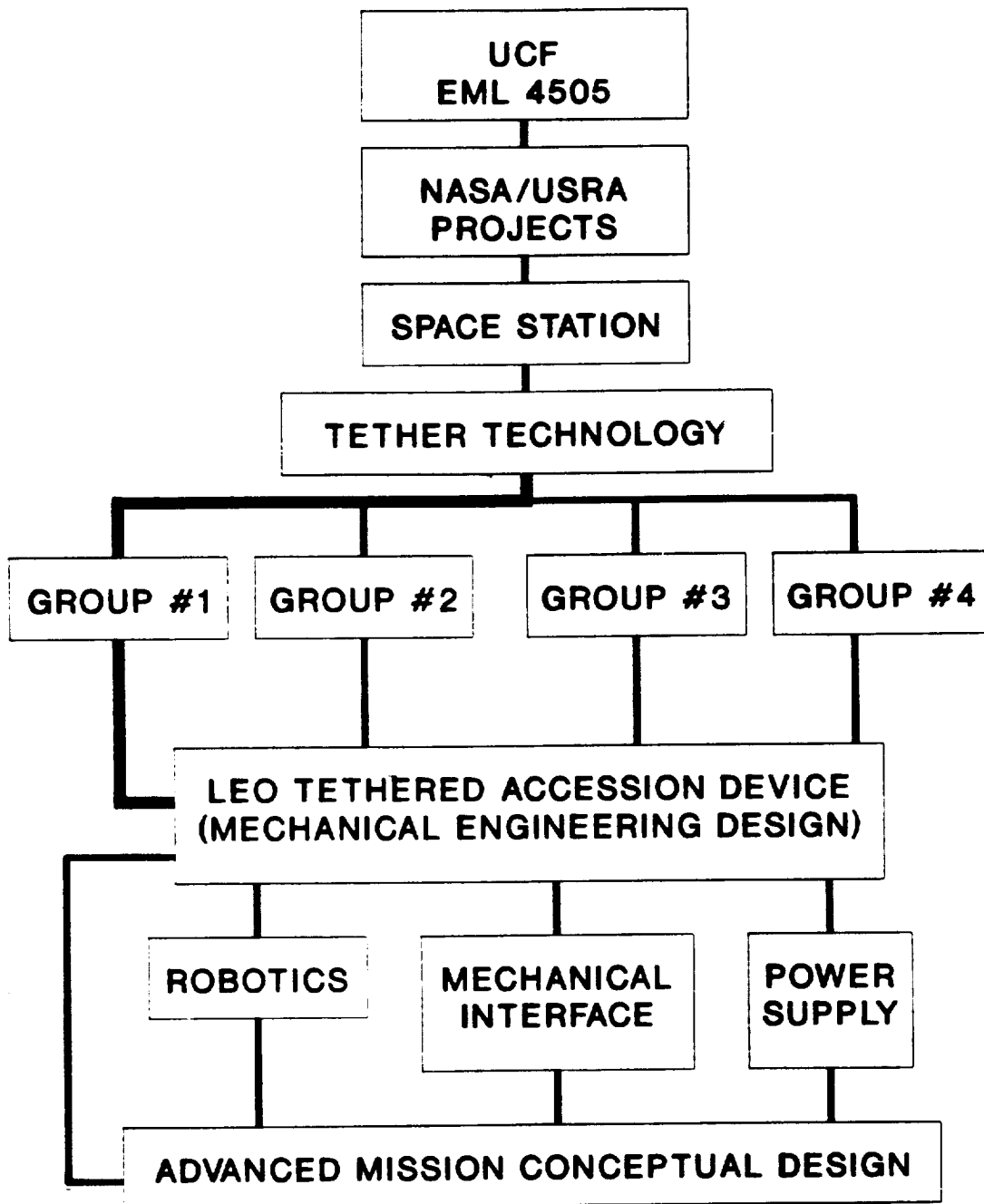


Figure 3.

design process. Second, the Specifying Goals phase addresses the design constraints, restrictions, and standards which must be met, no matter the design. This phase also defines what constitutes an acceptable solution to the design problem under observation. Third, the Determining Means phase stresses the development of candidate design solutions. At this point, Design Discussions are orally presented to distribute proposed design ideas. Finally, the Solution Optimization stage encompasses the evaluation of all design alternatives and the identification of the optimal solution(s). Subsequent to the Solution Optimization phase, a Design Review is conducted at Kennedy Space Center. Valuable insight on the proposed designs is provided and the information is utilized to best meet the needs and requirements of the space community.

## SECTION I.

### ELEVATOR CONFIGURATION DESIGN

#### DESIGN PHASE I.

- \* Offset Pallet
- \* Component
- \* Half Cylinder
- \* Dual Pallet
- \* Cylindrical
- \* Foldout

#### DESIGN PHASE II.

- \* Systems Elevator
  - Main Unit Shape
  - Horizontal Positioning Geometry
  - Horizontal Positioning Mechanism
  - Counterbalance Mechanism

## SECTION I. ELEVATOR CONFIGURATION DESIGN

### INTRODUCTION

Tether technology has yet to be fully tested in a space environment. The Tethered Satellite System (TSS) missions will be valuable in determining the feasibility of a tethered elevator.[4] Moreover, a TSS flight will be significant as a means of validating mathematical models and describing the dynamics, control, and key design factors for a tethered system and its components.[2] Here, general design considerations for one of these components, the tethered elevator, are introduced.

#### Mass

Consideration of the overall TECTS mass is crucial in the final design analysis. Financial and mechanical factors which include cost, stability, and effect on tether life are some of the main considerations for elevator designs. When cost is considered, larger masses are more expensive to place into orbit. Every attempt will be made to keep the elevator mass at a minimum during the design phase.

Tether life is an important design consideration and is inversely related to the elevator mass. The axial forces exerted by the drive mechanism on the tether will cause wearing due to the friction. The greater the mass of the TECTS the more wear and shorter the life span of the tether.

#### Tethered System CG Position

When an elevator weighing 5,000 kg (unloaded) is imposed on the tether, the CG can vary between 1639 meters to 1803 meters away from the SS, depending on whether the elevator is at the SS or the end mass, respectively. For the lowest microgravity level, the elevator should be positioned at 1666 meters from the space station. At this point, the elevator's CG will coincide with the CG of the tethered system.

#### Dynamics

When considering the mechanics of elevator operation, it is found that once the mass of the elevator is determined the acceleration of the elevator is only limited by the tension in the tether. Based on a SS mass of 250,000 kg and an end mass of 50,000 kg, the tension for various tether lengths is illustrated in Figure 1.1. With a tether length of 10 km the tension in the tether is 1700 N.[5] For an elevator mass of

## *TETHER TENSION vs. LENGTH*

SS = 250,000 Kg  
End Mass = 50,000 Kg  
Elevator = 10,000 Kg

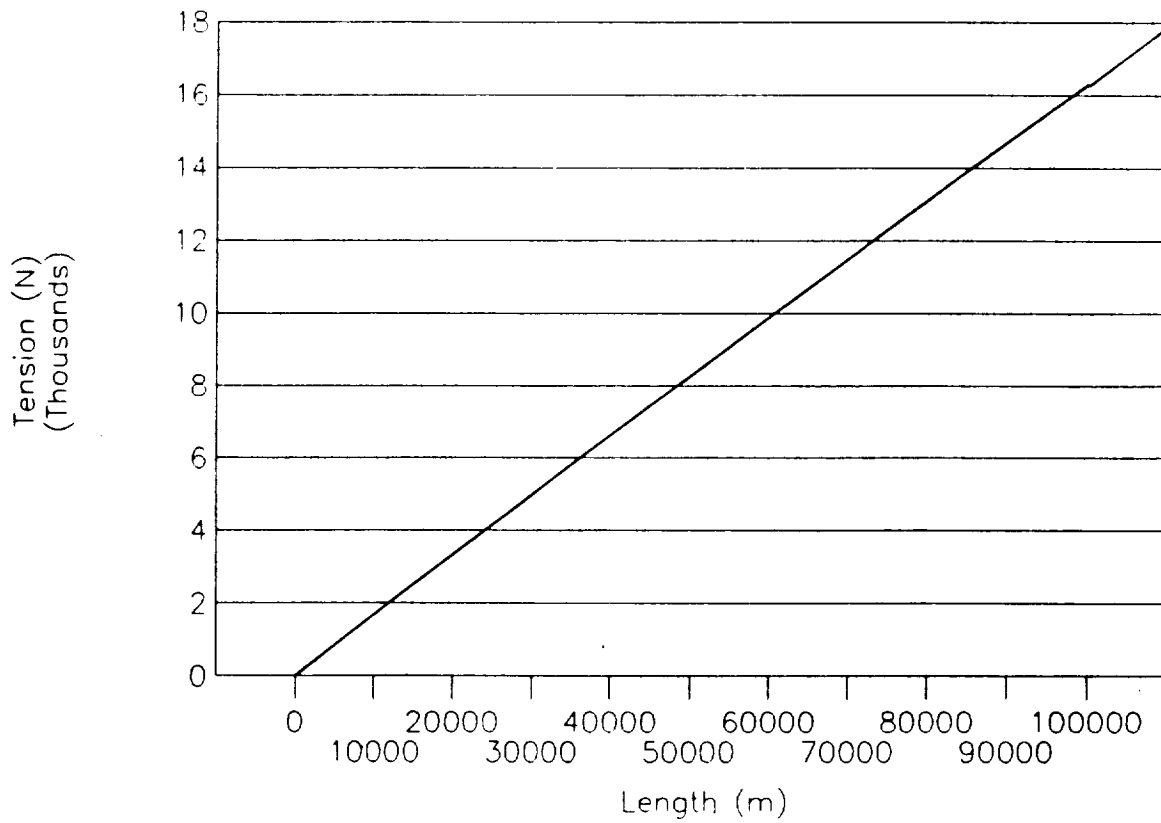


Figure 1.1



10,000 kg mounted on a 10 km tether, a maximum acceleration of  $0.17 \text{ m/s}^2$  is possible. This acceleration would allow for a 11.76 second rise time to a constant velocity of 2 m/s. Therefore the product of the mass of the elevator and the acceleration of the driver is limited by the tension in the tether.

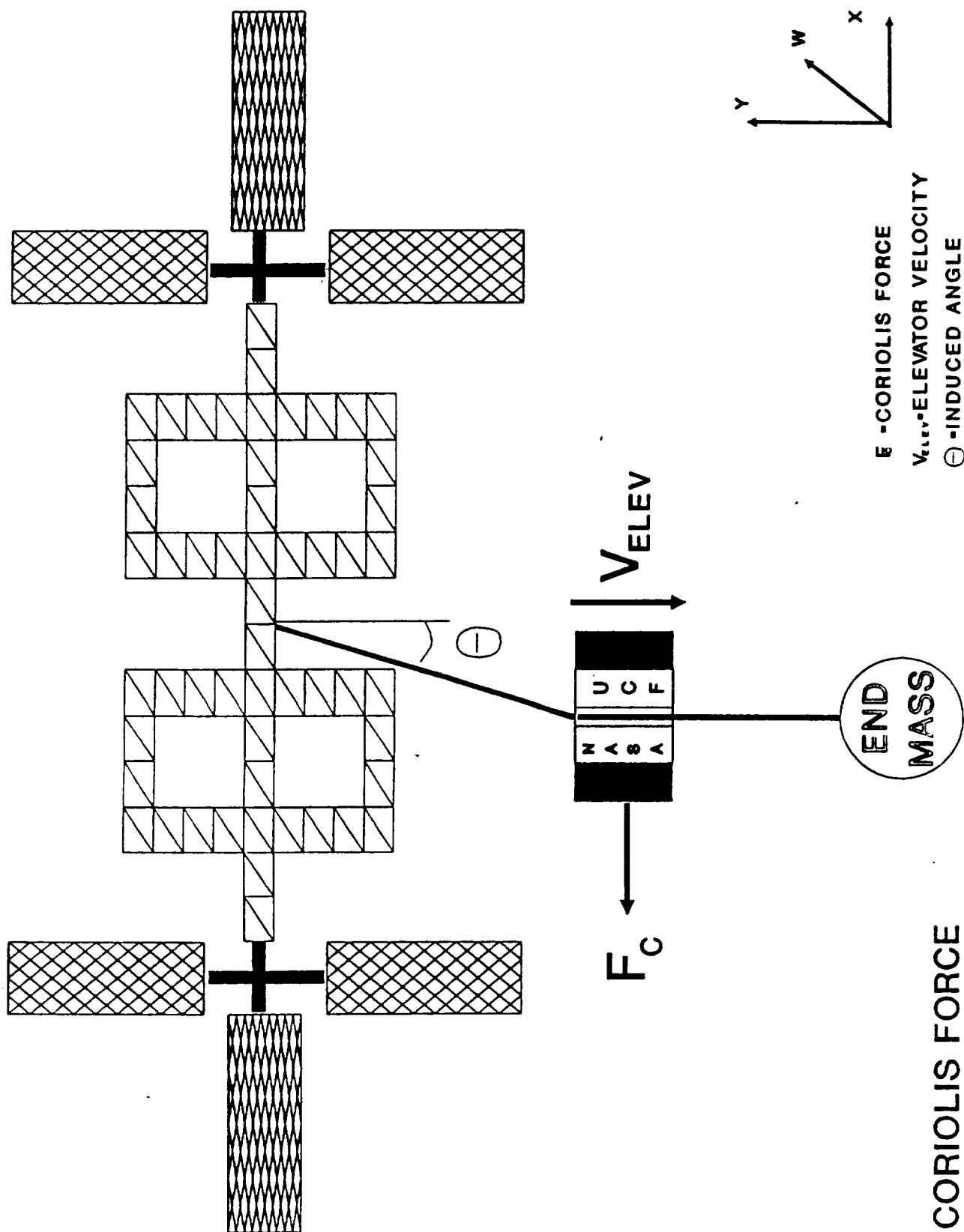
When the elevator is accelerated along the tether a force is created perpendicular to the tether due to its Coriolis acceleration. The Coriolis acceleration vector is perpendicular to the relative velocity vector of the elevator. This is easily seen from the equation  $2\mathbf{W} \times \mathbf{V} = \mathbf{A}_c$  and by using the right hand rule.

In order to maintain the dynamic disturbances within acceptable limits the TECTS will travel at a constant velocity not to exceed 5 m/s.[5] Tether lateral vibrations are induced by the Coriolis acceleration acting on the elevator as it moves along the tether. This acceleration is induced by the translation of a mass in a rotating frame of reference and is always perpendicular to the direction of translation.[5] "The Coriolis force, depending on the magnitude of the velocity, is as controllable as the velocity of the elevator is small. Velocity of the elevator will be a constant, compatible with the required mission time." [6] Governing equations for the velocity of the elevator have been derived and are listed in Appendix A for a more detailed analysis.

When the elevator is moving in the negative Y direction, the Coriolis force is in the negative X direction (Figure 1.2). This force can cause small librations which can disturb the axial alignment of the tether and create an angle ( $\theta$ ). By limiting the relative velocity of the elevator these librations can be reduced, since the Coriolis force is directly proportional to the elevator's relative velocity.

Not only are lateral vibrations a concern, but longitudinal vibrations can also affect the performance of the system. If the driving force of the elevator exceeds the tension force in the tether, the tether will be reeled up instead of the elevator traversing down it. This will allow slack in the tether, causing longitudinal vibrations. To eliminate this potential problem, the elevator acceleration will be limited so that the driver force does not exceed the tension force. This problem is due to the fact that the driver force is directly proportional to the acceleration of the elevator as seen from the equation,  $F = (M_{\text{elev}}) \cdot (A_{\text{elev}})$ .

The following table is a list of some of the elevator's performance parameters. To see a complete set of calculations, and the logic behind them, the reader is referred to Appendix A.



INFLUENCE OF CORIOLIS ACCELERATION ON ELEVATOR

Figure 1.2

Angular Velocity	.00115475390312 rads/sec.
Maximum Allowable Acceleration	.06776 m/s <sup>2</sup>
Time to Accelerate/Decelerate	29.5 sec.
Time to Traverse Tether	1.4 hrs.
Coriolis Acceleration	.004619 m/s <sup>2</sup>
Coriolis Force	115.5 N
Tether Tension	1694 N
Tether Angle	3.97 deg.

NOTE: Some of the calculated values, which are indicated in the table above, are dependent on the weight and position of the elevator. The above values were calculated using a 25,000 kg elevator at a position of 29.5 meters from the space station.

### Vibration Prediction Analysis

Vibration analysis is of considerable importance due to its impact on the SS through the tether. Unfortunately, it is also one of the most difficult areas to predict. Some studies have been performed in this area by the University of Alabama in Huntsville (UAH) for Marshall Space Flight Center.[6] Experimental models have been developed to test for several parameters, including vibration. Instrumentation such as strain gages and accelerometers are used to record various values of acceleration, velocity, and vibration. In a paper written by Dr. Enrico C. Lorenzini entitled "Analytical Investigation of the Dynamics of Tethered Constellations in Earth Orbit," a new motion control law was developed.[7] A previous law called the Modified Hyperbolic Tangent Control Law was modified to come up with the Mirror Image Motion Control Law (MIMCL). This new law has been used in conjunction with the simulation runs performed in Huntsville at the UAH. Modeling of tether vibrations was also performed for the system. A detailed software system was developed to handle a complex matrix setup. For further information on vibration predictions, it is recommended that a copy of reference [7] be obtained.

Vibrations to the structure of the elevator from the driver motor may cause problems to certain experiments and must be damped out. This will be done to keep excess vibrations from disturbing sensitive experiments on the trip to and from the SS. One possible solution to this problem includes the use of a three dimensional damping mechanism mounted between the overall structure of the elevator and the drive motors. Some of the proposed damping mechanisms are:

1. Hydraulic
2. Gas
3. Spring
4. Electromagnetic
5. Electric Field

During elevator motion there are control forces exerted from the elevator to the tether in order to reach and maintain the desired velocity profile. These "accelerating" and "decelerating" forces act on a line through the tether axis and constitute longitudinal modes of vibration. The longitudinal modes of vibration have short periods in the axial direction and should be easiest to control.[7]

#### Elevator CM Position

In addition to these forces from elevator motion, the directional gravity acceleration along the tether will act on a line through the center of mass (CM) of the elevator. This gravity acceleration level could vary anywhere from  $10E^{-8}$  g at the CG of the tethered system to as high as  $10E^{-3}$  g at the tethered end mass.[5] In Figure 1.3, it can be seen that drive forces combined with gravity acceleration forces could induce a moment on the elevator causing additional longitudinal vibration of the tether. The longitudinal vibrations induced by the drive forces will always be present due to the frictional driver mechanism.[8] However, the longitudinal forces created by the offset CM can be controlled by the design.

#### Other Design Considerations

Robotics on board the elevator allow for hands-off servicing of space bound equipment. For successful elevator operation robotics must accent the TECTS design. Location of the elevator's RMS must provide accessibility to equipment mounted on the TECTS, while having the ability to interface with other SS support systems. Several designs incorporate a track system for RMS adjustment while others hold the RMS fixed. In the final consideration, all designs will use the most practical RMS configuration.[9]

The TECTS design will include an independent power source to operate the drive mechanism, the RMS, and to aid in transmitting information.[10] Room on the elevator is valuable, and the design must efficiently house the power source equipment. The different power source considerations will require varying space on board the elevator. The elevator must include appropriate interfaces between the power supply and the various loads. These power connections will be universal to allow for optimal component interfacing. The drive mechanism and the RMS will dictate the maximum available power that will be supplied by the power source.

A datum link will also be necessary in order to provide remote communication between the SS and elevator. Two types of datum links are possible. One is an umbilical cord

## *EFFECT OF CENTER OF MASS ON ELEVATOR*

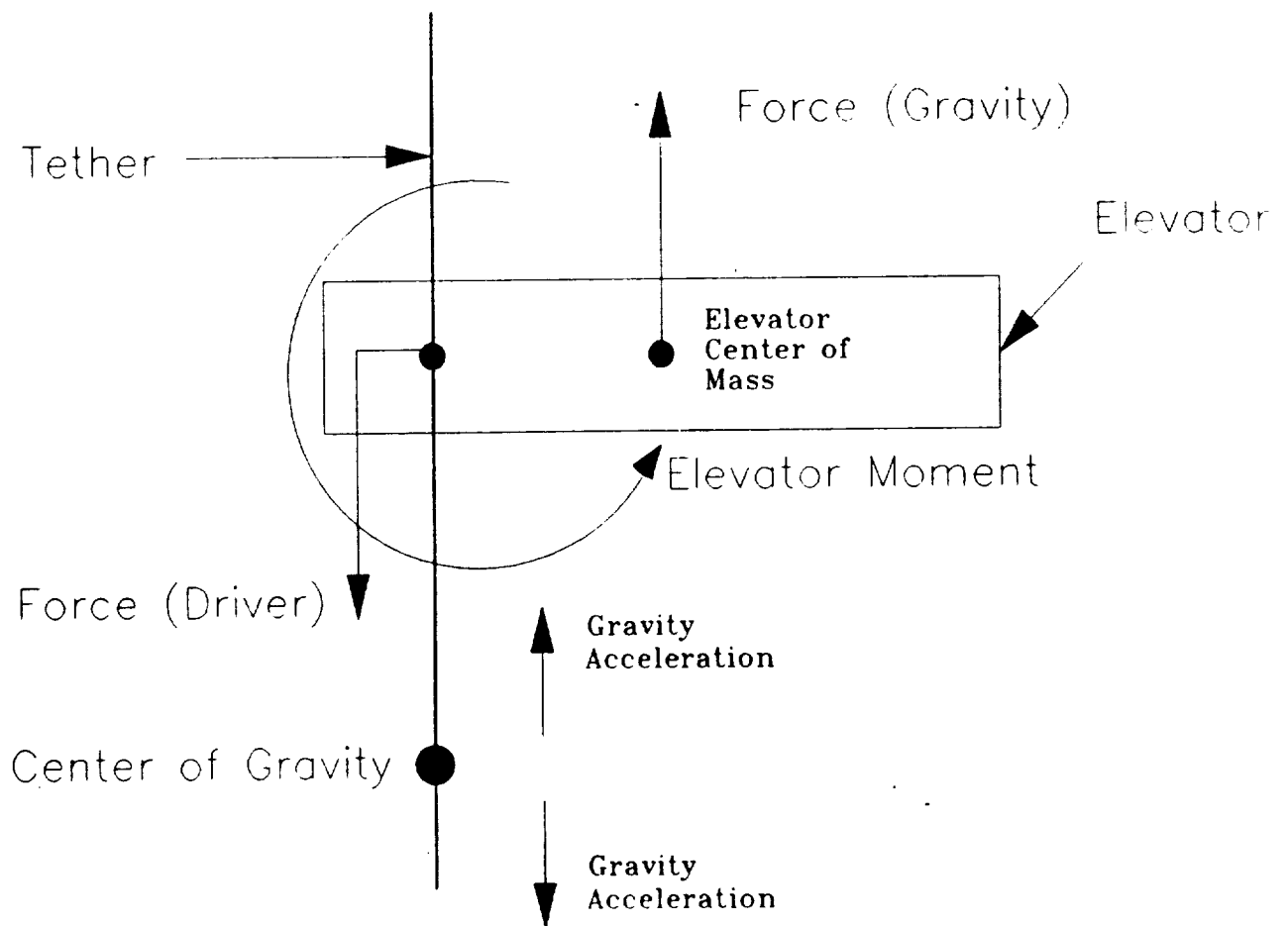


Figure 1.3

attachment for data relay by means of a fiber optic cable for signal transmissions. The second alternative would be a remote data relay that would use S-Band or other type of cordless data transmission.[4]

## Function of Hardware

The function of each of the systems must be defined before the design process can begin. The systems of the TECTS are as follows:

1. Main Unit
2. Shielding
3. Horizontal Positioning System
4. Counterbalance System
5. Drive System
6. Attachments
7. Data Transfer System
8. Robotics System
9. Power System

A brief discussion of each of these systems' functions is now given.

The main unit shall house, support and/or protect all systems on board the TECTS. The maximum dimensions of the main unit shall not exceed the envelope of the Orbiter cargo bay. The minimum dimensions shall be limited by the size and orientation of the internal and external components. The structural integrity of the main unit must be sufficient to support all components mounted to the inside of the main unit. The frame should be reinforced in mounting areas for pallets, the robotic arms, and any other external components. The frame must also be compatible with, and provide mounting for, all required shielding.

The main unit shall be equipped with some type of shielding. The shielding shall be insulated so that the 500 degree temperature change associated with LEO is not experienced within the main unit. Specific temperature requirements should be stated when determined from internal component limitations. Also, shielding will provide protection from space debris, a factor that could be very damaging to internal components. The primary purpose of the Horizontal Positioning System is to help offset any moments created by uneven mass distribution on the TECTS. A gearing mechanism would interface with a moment sensing device and automatically move the elevator relative to the drive mechanism and tether axis. It would also insure that the CG of the TECTS is as close as possible to the tether axis thus minimizing external disturbances.

A system which could act in conjunction with the horizontal positioning mechanism, or by itself, to insure proper center of mass (CM) positioning, is a counterbalance system. This system would position pallets, experiments, and modules closer or farther from the main unit in order to acquire the desired CM location.

The TECTS shall be moved vertically along the tether by the Drive System. All components of the drive system shall be housed within the main unit. The drive mechanism is discussed in greater detail in Section III. The attachments will be compatible with those on the SS and the Space Shuttle to insure that all systems exhibit commonality. For pallet mounting, various types of attachments could be available by mounting one of various plates to the counterbalance system. Each plate would have a certain type of attachment in a configuration compatible with the pallet mounting points. Experimental, waste, or transportation modules shall be configured to mount to the pallets in the same manner. All operating systems shall be controlled remotely by signals sent from the SS control station via the data link system. The data link antenna shall be mounted to the outer surface of the elevator and must be able to withstand the external temperature change. The signals will then be transferred to the central processing unit (CPU) housed within the main unit. The CPU will convert these signals to the desired work by the applicable system. The robotic system shall provide the TECTS with on board manipulation capabilities for the pallets/modules, as well as, maintenance support for the TECTS by removing and replacing faulty components. This will require that all components of the TECTS be space removable units (SRU's). The robotic arms must be able to access all SRU's and all pallet areas. The data link and robotic systems are discussed in detail in Section II.

The power system must provide enough power to propel the elevator, as well as, supply power for the operation of all TECTS systems. Since it is unlikely that external elevator mechanisms will be operating while the elevator is traversing the tether, the loads can be applied where needed and should stay relatively constant during normal operation. The power system shall mount inside the main unit and must be safe to personnel. Details of the power system are discussed in the design discussion presented in Section IV.

The above areas which will be investigated further in this report include the design of the main unit, shielding, positioning systems, and the counterbalance system. Design ideas for each of these areas are discussed in the following sections.

## DESIGN PHASE 1. ELEVATOR CONFIGURATION DESIGNS

Given the aforementioned design parameters, six designs were conceived. These designs vary in their form and provide a variety of solutions to the problems encountered by the TECTS. Each design should provide a feasible solution for the tethered elevator. By presenting more than one alternative, certain outstanding features will arise that can be included in any future designs.

### Chapter 1. OFFSET PALLET CONFIGURATION

The Offset Pallet Configuration consists of a single pallet, similar to the pallets used to secure payloads aboard the current space shuttle. (See Figure 1.4) This method of standardization would enable the elevator to load a payload pallet from the shuttle and transport it to the SS as well as to house experiments and transport other types of SS payloads. The pallet will be attached to the elevator assembly via a common plate. This plate will be multi-functional and the drivers will be attached at either end of its Y-axis. Grapple fixtures will also be affixed at these locations to prevent collision of the elevator with the SS or end mass, and provide the means of a rigid attachment to these tethered bodies. Payload support interfaces are housed by the plate, and the counterweight support structure originates at this point.

The counterweight is placed on the opposite side of the elevator with respect to the tether and will offset any moments created by payloads or experiments which are attached to the pallet. This counterweight would serve as the power unit if nuclear or chemical power generation is utilized. The datum point for the RMS and datum link will also be on the counterweight.

The counterweight is attached to the common plate by three telescoping struts arranged in a triangular fashion as shown in Figure 1.4. This arrangement provides a CM adjustment in the X, Y, and Z planes. Although this is a rather complex system, precise control can be attained with the use of gravitational accelerometers to provide input to computer software which will in turn control the actuation of the telescoping struts. With this tri-strut arrangement, tether access is restricted to the side of the elevator with only one strut. This strut must have the capability to be easily detached and attached with the elevator's RMS.



## OFFSET PALLET

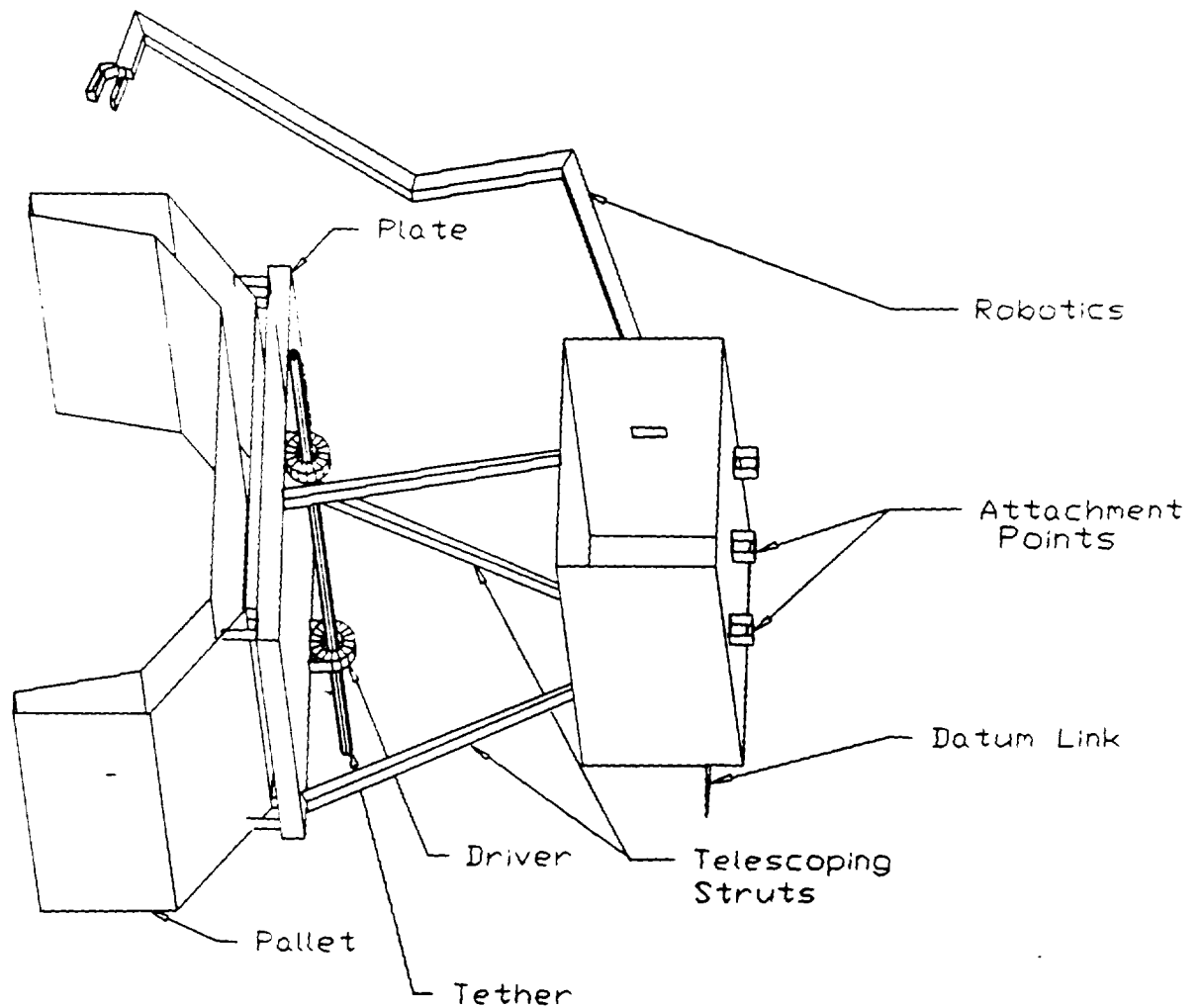


Figure 1.4

## Chapter 2. COMPONENT ELEVATOR

The Component Elevator consists of a central structure on which a plate and main operational unit are mounted. (See Figure 1.5) The central structure consists of a dual worm gear slider assembly. The worm gears allow for adjustment of the tether attachment point in a plane orthogonal to the tether. The worm gear slider assembly will be used to move the tether to the CM of the TECTS. The drivers will be located at a point common to both worm gears and will be connected by a rigid bar assembly to keep drive forces axial to the tether. This allows for pitch angle adjustment of the elevator with respect to the tether.

The main operational unit will contain a datum link, attachment points, power unit, and robotic device. The datum link will be used to control and monitor TECTS operations such as remote manipulation of the robot arm, elevator alignment with SS, and experimentation monitoring.

Attachment points will be universal and allow for various structures to be easily attached and removed from the elevator with minimal EVA. An area will be provided so that power devices can be connected to the main unit permanently, e.g. solar arrays or power plants. To increase stability of the elevator while in motion the robotic arm will be parked in a locked position between the two masses as shown in Figure 1.5.

## Chapter 3. HALF CYLINDER CONFIGURATION

The half cylinder TECTS design will consist of a permanent cut cylinder body attached to a telescoping support structure. (See Figure 1.6) The driver mechanism which will attach to the tether will be placed at the end of the elevator support structure. A telescoping support structure will be utilized in order to adjust the center of mass or alter the pitch angle of the elevator with respect to the tether. The drivers will be attached to each other by a bar so that they will remain in a parallel alignment on the tether.

A grapple fitting will be placed on each end of the elevator to prevent collisions and to give a rigid attachment point for docking with other tethered bodies. Other attachment points will be placed on the elevator face opposite the tether, e.g. longeron attachment fittings. Hardware for attitude measurement and control will be placed on the inner face of the elevator near the support legs to take advantage of the structural stability in this area. An antenna or directional dish will be connected to the leading edge of the half cylinder, as shown, to allow for data

## COMPONENT ELEVATOR

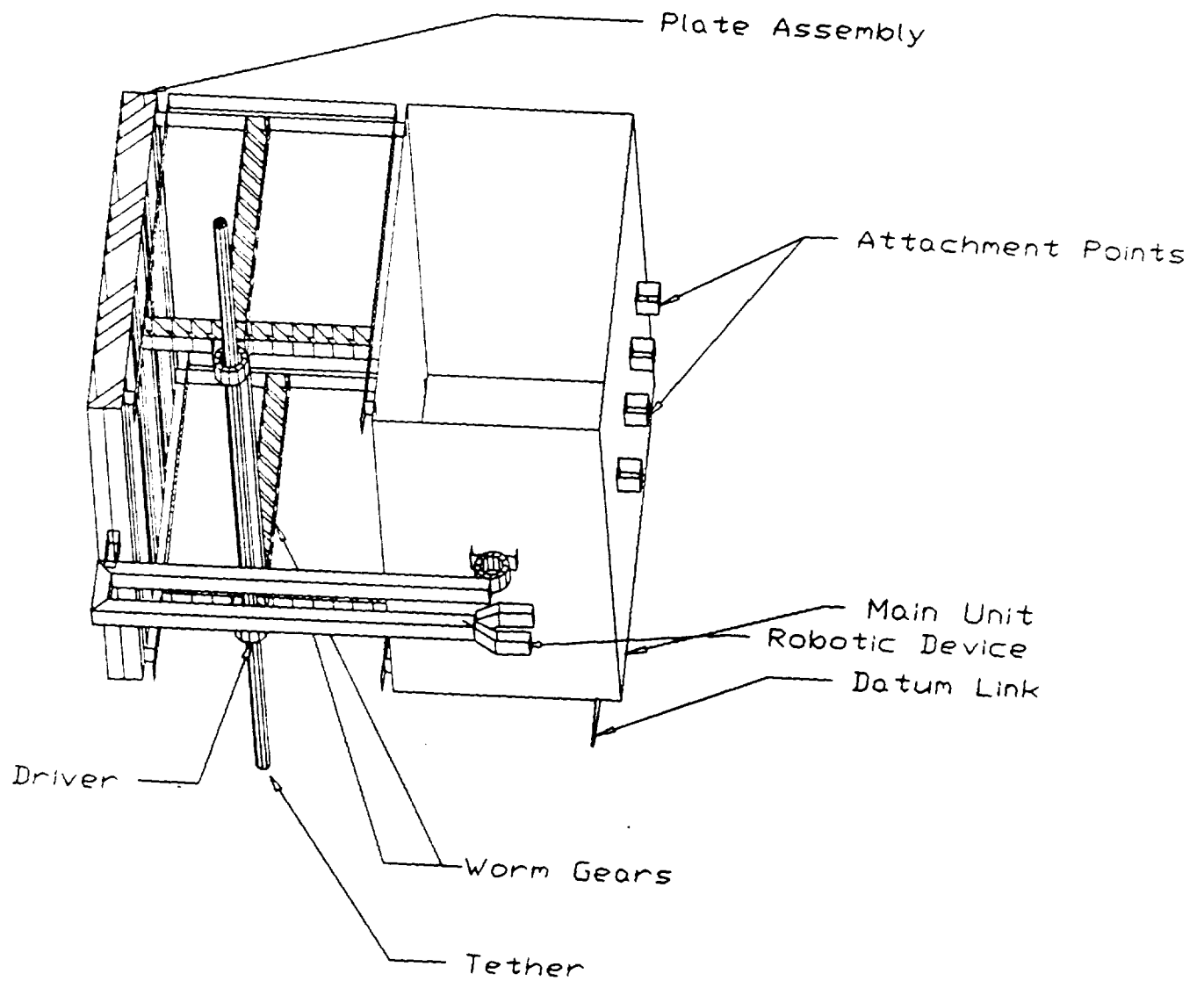


Figure 1.5

## HALF CYLINDER

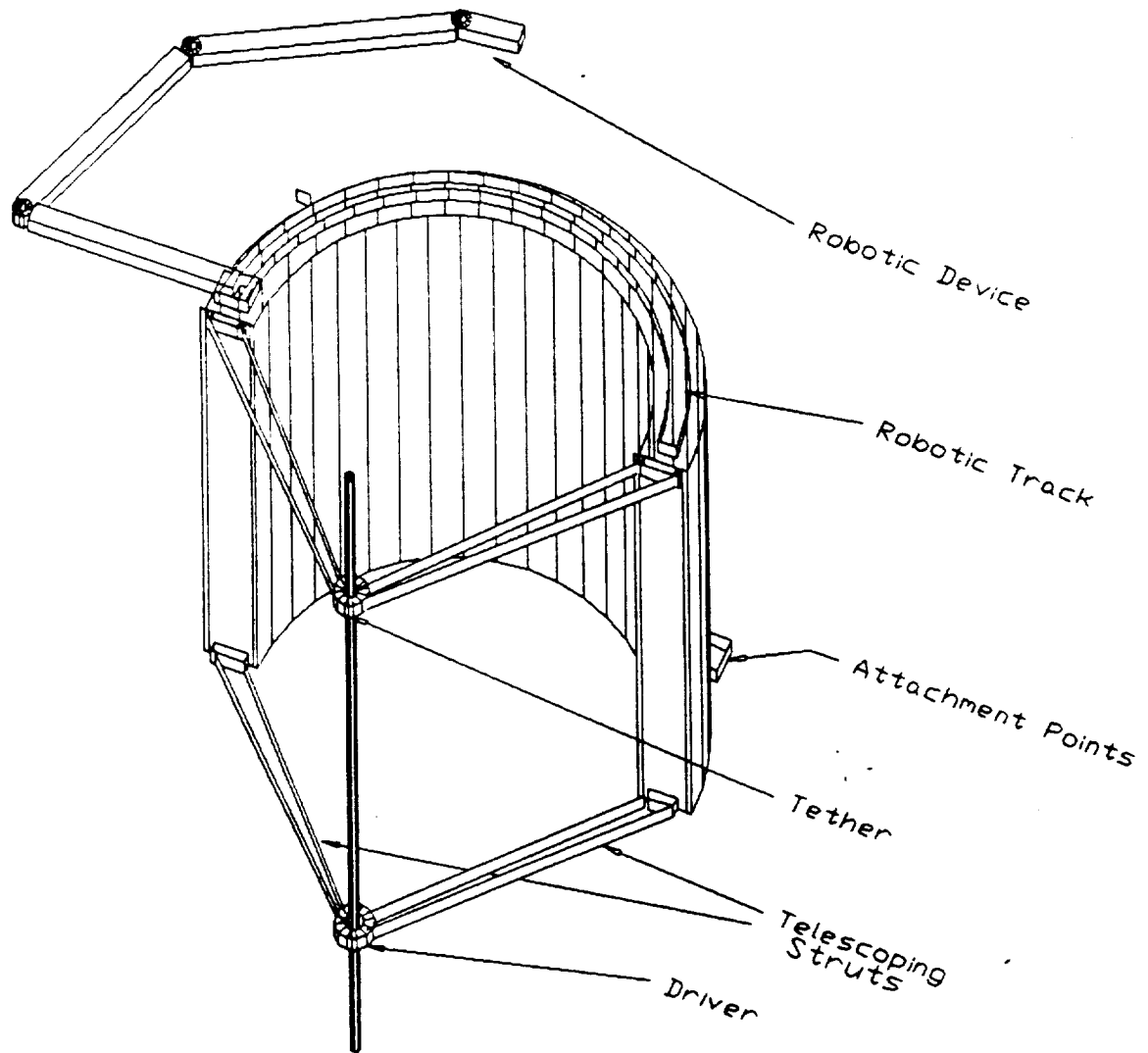


Figure 1.6

transmission and robotic control.

Radiators will be placed on the lower side of the elevator and space will be made available for solar panel attachment, or other power unit, just above the radiators. A robotic device is attached to the upper edge of the elevator and is able to translate around the edge on a track. The robotic device shown in Figure 1.6 is in the parked position.

#### Chapter 4. DUAL PALLET ELEVATOR

The Dual Pallet TECTS design will consist of two pallets similar to the pallets designed for the Space Shuttle's cargo bay. (See Figure 1.7) The pallets will be connected to the tether by a tether positioning system. The tether positioning system will be composed of two structures, one on the top and one on the bottom, as shown. These structures will be able to adjust the position of the elevator with respect to the tether.

An antenna or directional dish will be attached to one of the pallets, as shown, to allow for data transmission and robotic control. Photovoltaic panels will be mounted if solar power is used. If an alternate form of power is used, such as nuclear or chemical, the equipment needed will be attached between the two pallets.

If robotics are necessary the robotic design will be attached to one of the pallets at a fixed point. The most convenient position on the pallet for robotic operation has not been determined. The position of the robotics in the figure is arbitrary.

#### Chapter 5. CYLINDRICAL CONFIGURATION

The Cylindrical Elevator configuration consists of a cylindrical structure with a small wedge removed for attachment of the tether to the center of the elevator. (See Figure 1.8) Two drive mechanisms will be employed inside the elevator along the vertical axis. Drive mechanisms will be located at the top and the bottom. Attachment points will be provided for the attachment of experiments and operational equipment. A control link may be fixed to the exterior of the cylinder. Grapple fixtures will also be affixed at either end of the elevator's vertical axis to aid in stability. The robotic device will be allowed to rotate around the elevator on a track as shown. The main cargo area will be limited to the outside of the structure due to the small wedge-shaped opening.

## DUAL PALLET

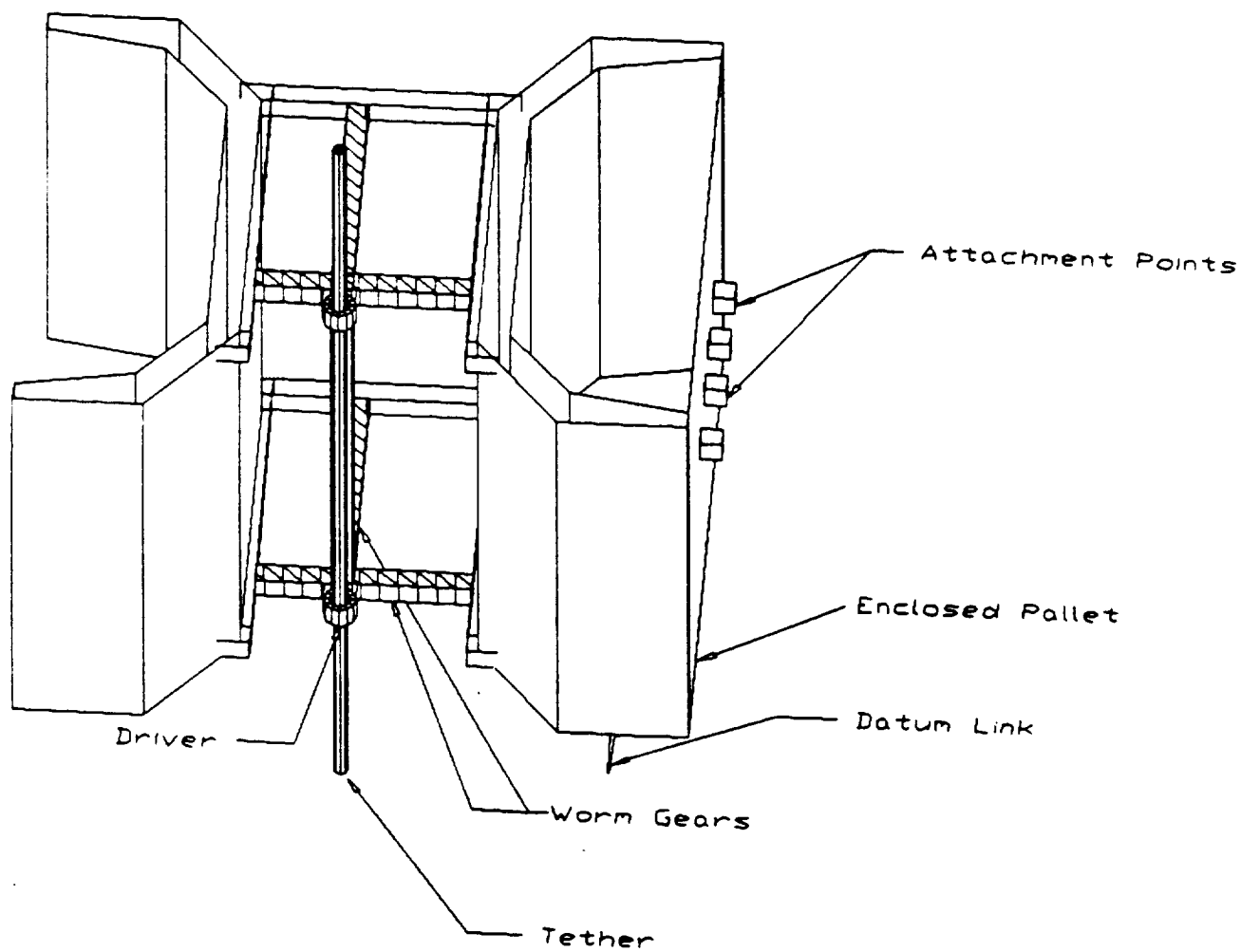


Figure 1.7

## CYLINDRICAL CONFIGURATION

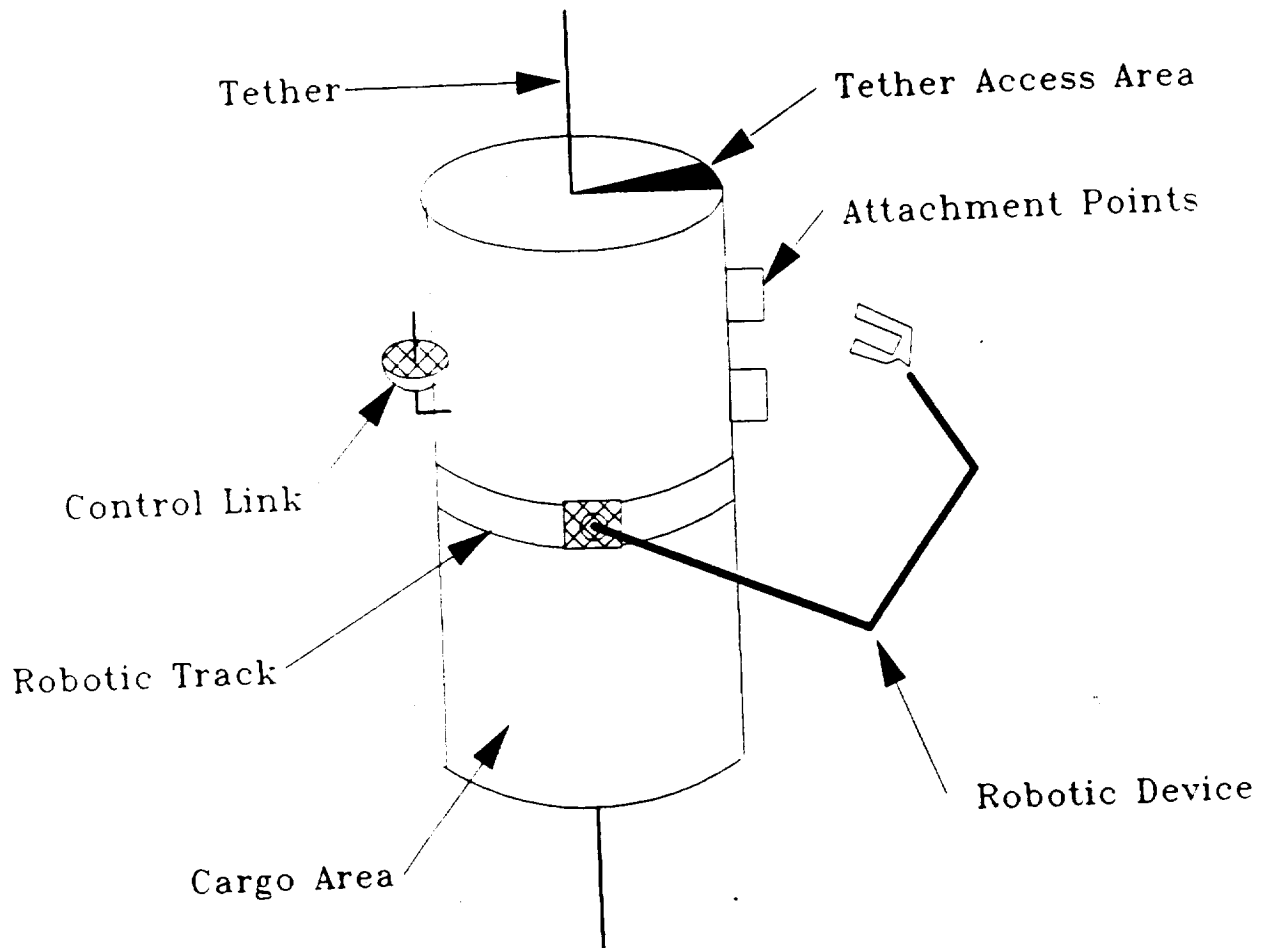


Figure 1.8

## Chapter 6. FOLD-OUT CONFIGURATION

This elevator design incorporates a rectangular configuration. (See Figure 1.9) Similar to the Cylindrical configuration, this design is simple in that it has a fixed tether/elevator orientation. The CM is adjustable only by the arrangement of the experiments and payloads. Dual drivers are employed at either end of the elevator's vertical axis to aid in stability and are enclosed within the elevator's structure. Fold-out panels on the front of this design allow for an increase in accessibility to the elevator's interior. This would enable the elevator's interior and exterior areas to be used for experiments and payloads.

## Chapter 7. DESIGN CONFIGURATIONS SUMMARY

The goal of the TECTS design process is to create a system which operates remotely on the SS tether. This design must act harmoniously with existing SS designs and perform all designated tasks required of the TECTS. Research and analysis was performed on various designs with special attention given to the main design considerations.

Six design concepts were brought forth for consideration and their forms varied greatly. Ultimately, a compromise between simplicity and versatility must be made using one specific design or a composite of designs proposed. Finally, it is important to realize that the TECTS is a supplement to the SS's array of functions and its successful integration and synergistic relation is crucial to the effective operation of the SS.

## Chapter 8. ELEVATOR CONFIGURATION OPTIMAL SOLUTION - DESIGN PHASE I.

In order to achieve an optimal design for the TECTS, the evaluated design configurations and the design parameters were analyzed via a decision matrix, (See Solution Matrix 1.1). This matrix contains numbers from zero to twenty in which zero is the least applicable and twenty is the most applicable. These numbers relate each design consideration to the individual design parameters. The parameters are given a weighting factor to represent their importance relative to each other. The weighting factor ranges from one to nine with the latter being the most significant. To determine the optimal design, a summation of the applicability number multiplied by the weighting factor is performed. This yields a numerical representation for each design and is used for comparison. The more preferable a design is, the higher this value will be.



## FOLD-OUT CONFIGURATION

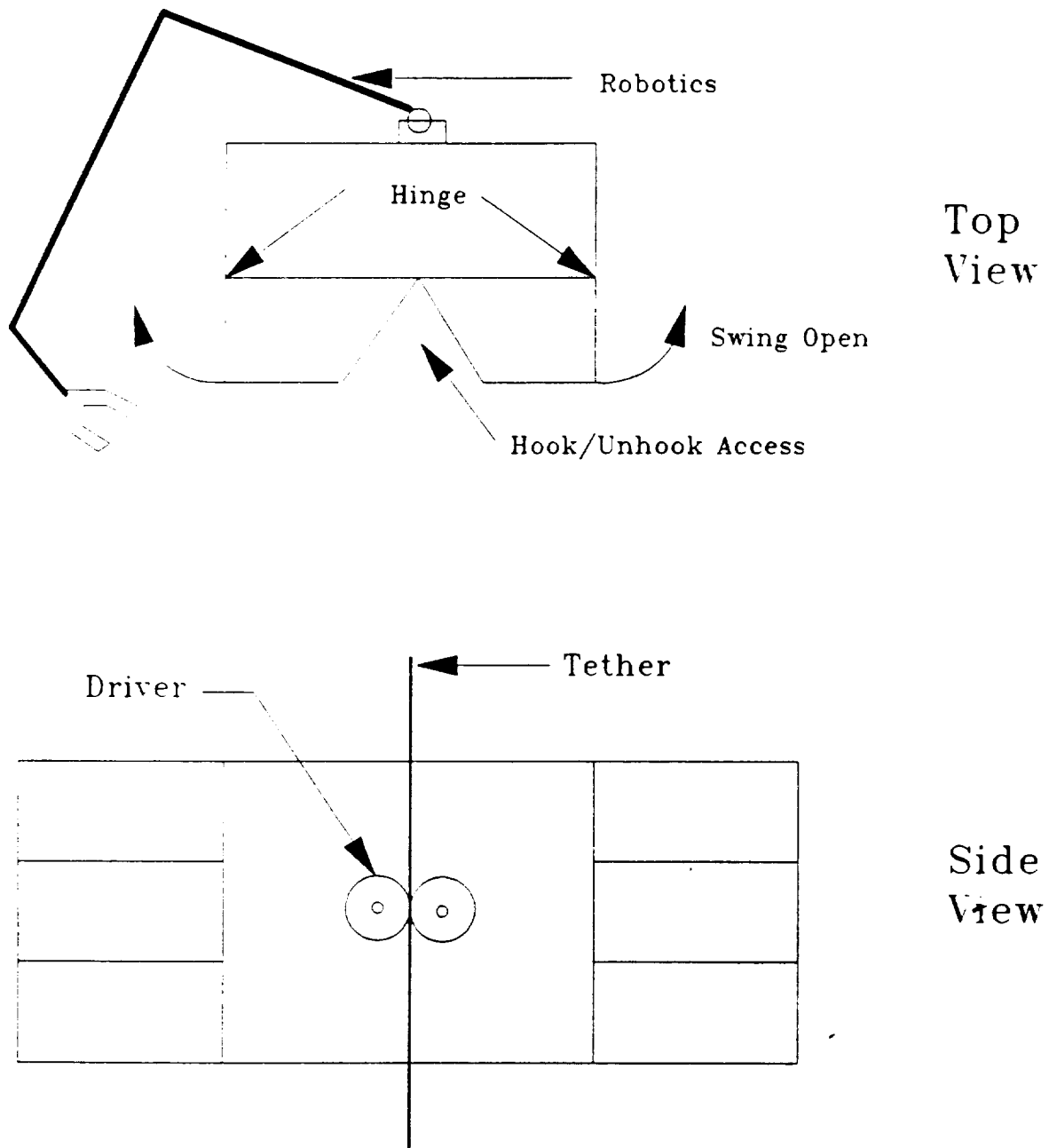


Figure 1.9

The same procedure was used to determine the optimal method for transmission of data to and from the elevator. Two alternatives were considered in the decision matrix, (See Solution Matrix 1.1). One method is data transmission through a fiber optic slack tether attached from the SS to the elevator. The second type of datum link is remote transmission by S-Band or other frequency.

The optimal datum link design selected in the decision matrix was the remote relay. The parameters which influenced this decision were SS disturbance, hook/unhook, robotics, and durability. It was determined that a slack tether would transmit disturbances to the SS more than a remote relay. A slack tether would also hinder the hook/unhook operation, the use of robotics, and the stability of the TECTS. The fiber optic umbilical is also less durable than a remote relay.

The optimal elevator design selected by the decision matrix was the Component Elevator, (See Figure 1.5), with Cylindrical and Offset Pallet Elevators second and third, respectively. The Component Elevator parameters most heavily weighted in the decision matrix were stability, accessibility, payload interface, center of mass adjustment, and maintainability.

The Component Elevator design allows for optimum accessibility to experiments, payloads, and operating equipment. The design consists of a central box structure to which pallets are attached. The pallets have large surface areas which can be easily reached. On the central structure, where payloads are to be connected there will be numerous universal attachment points. All but a small surface area of the pallet will be accessible to allow for optimum payload interfacing. Payload interfacing and interaction are factors of design geometry and built-in operational functions. The robotics on board the elevator combined with the elevator's exceptional accessibility and payload interfacing should eliminate the need for EVA's to deploy the TECTS.

The Component Elevator design originated into its present form as follows. An initial design was proposed which incorporated the pallets used in the shuttle's cargo bay. Several designs were formulated from the initial configuration. A Dual Pallet design looked promising due to its large payload capacity and was studied further. A CM adjustment device was added at the point of tether attachment. The CM adjustment mechanism consisted of two perpendicularly mounted worm gears which allowed for two dimensional motion. The combination of two such devices gives added angular adjustability, unlike several of the other designs considered, i.e. Cylindrical and Fold-Out. The removal and replacement of pallets loaded with experiments and payloads was desired, so a centrally located structure

was designed which allowed for ease in manipulation of the pallets. The central structure would house the drive mechanisms and other equipment thus improving protection from the environment.



## DESIGN PHASE II. SYSTEMS ELEVATOR CONFIGURATION

For the Systems Elevator the design has been broken into the areas of shape, shielding, horizontal positioning geometry, horizontal positioning mechanism, counterbalance system, and vibration damping device.

### Chapter 9. MAIN UNIT SHAPES

The main unit shapes that were investigated include a square, a rectangle, a pentagon, an octagon and a wedge. Each of the shapes should be compatible with any of the horizontal positioning geometries and mechanisms within the elevator.

#### 9.1 Square

First, the square shape is probably one of the simplest designs being considered for the elevator's main unit. (Figure 1.10) An advantage of the square shape is simplicity of the structural and shielding requirements. Disadvantages of the square elevator include a small volume to surface area ratio and concentrated stress areas which will occur at the sharp corners. These stress areas could be alleviated to some degree by rounding all sharp corners.

#### 9.2 Rectangle

The second shape being considered is the rectangle. (Figure 1.11) This shape provides the greatest movement along the moment axis. Like the square, the rectangle also provides simple structural and shielding requirements. Disadvantages are the same as for the square shape elevator.

#### 9.3 Pentagon

The third shape that is being considered is the pentagon. (Figure 1.12) The pentagon has a better volume to surface area ratio than the two previous shapes. It provides lower stress concentration areas with the larger corners; and also provides the RMS with easy access to its internal parts, since the elevator's surface structure is at more shallow angles. Disadvantages include more complex structural and shielding requirements.

#### 9.4 Octagon

The fourth shape that is being considered is an octagon. (Figure 1.13) Although it is not shown in the figure this

## *SQUARE CONFIGURATION*

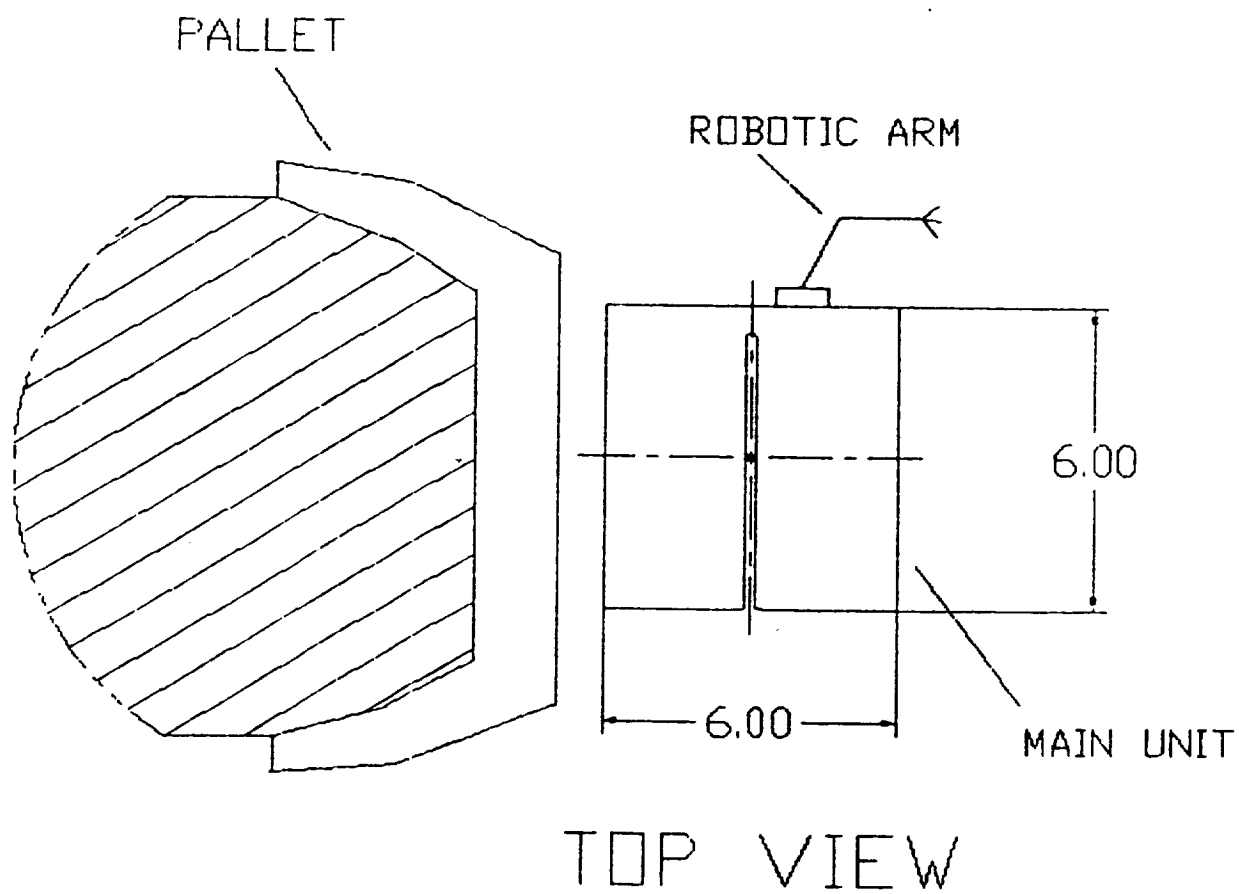


Figure 1.10

## *RECTANGULAR CONFIGURATION*

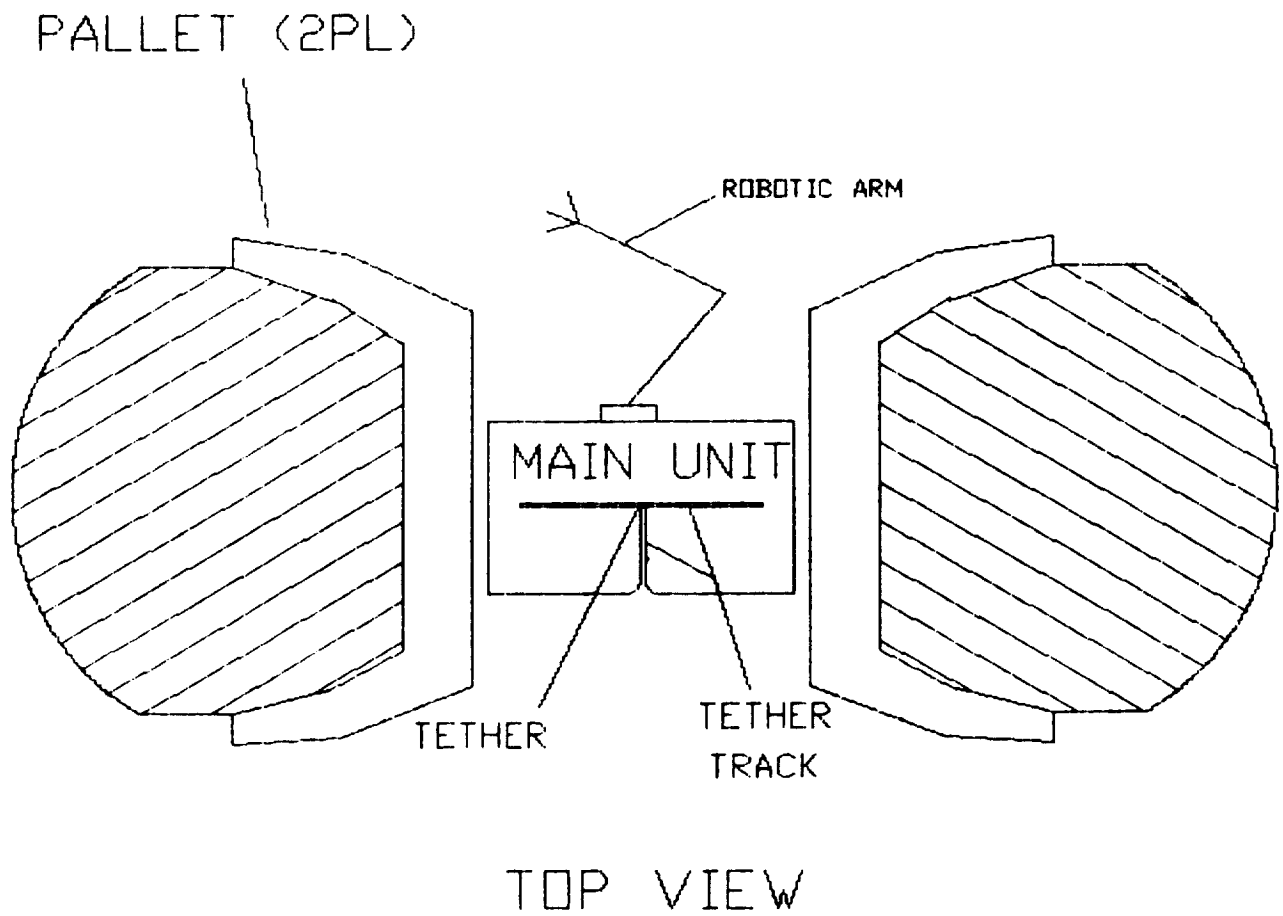


Figure 1.11

## *PENTAGON CONFIGURATION*

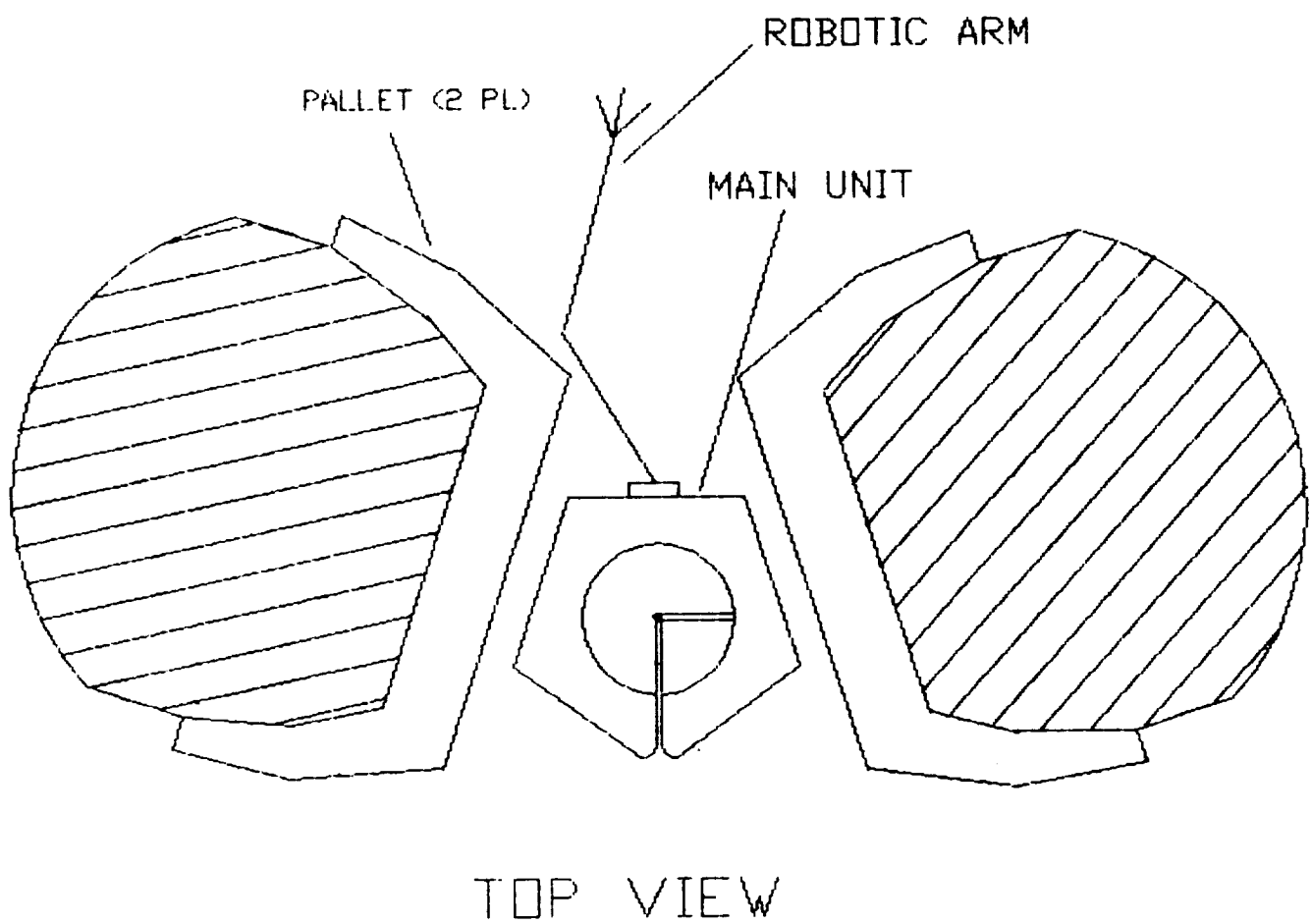


Figure 1.12



## OCTAGON CONFIGURATION

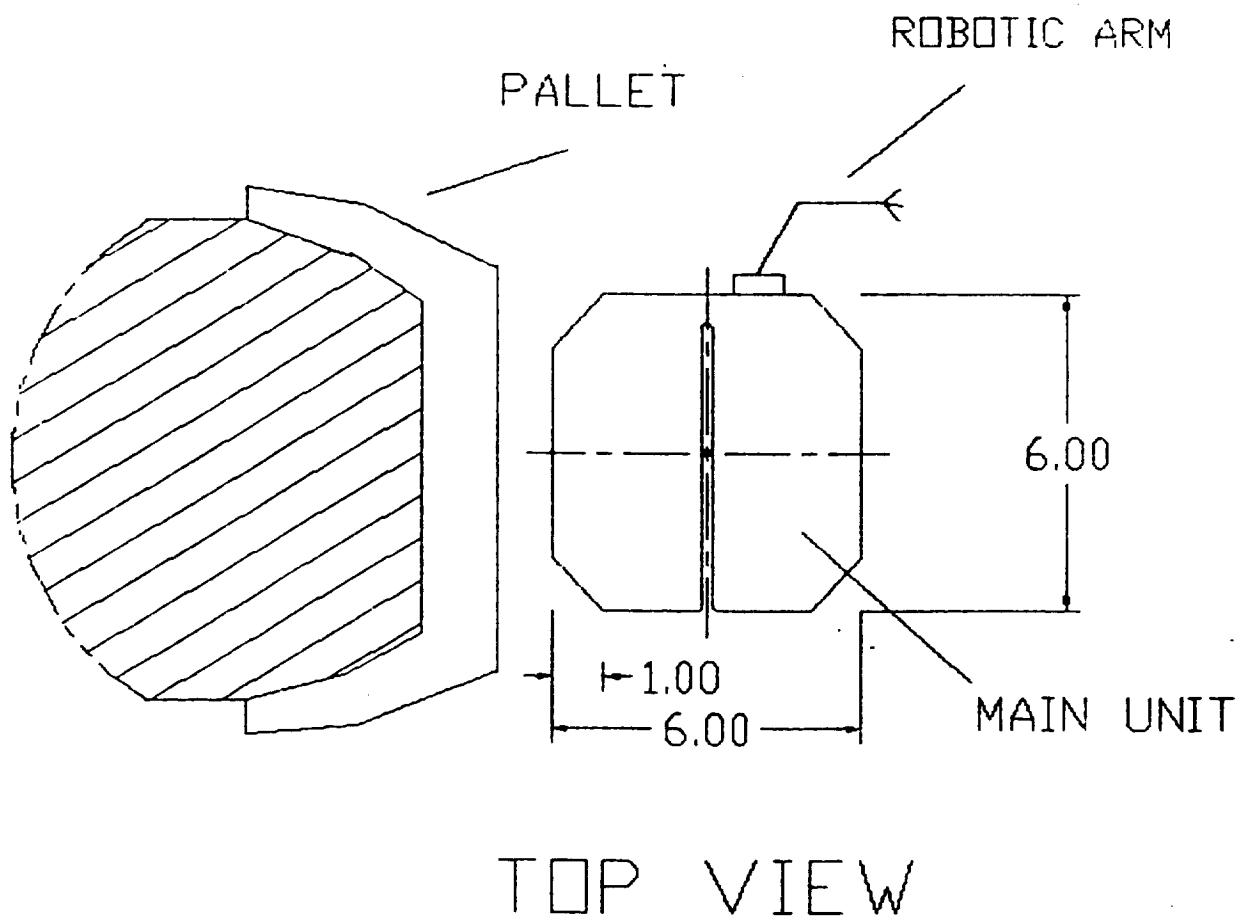


Figure 1.13

shape is consistent for every view. It also provides a good surface area to volume ratio and lower stress concentrations. This design offers many unique hardware mounting possibilities. In addition, the increased number of sides provide the robotic arm with easy access to all internal parts. A disadvantage is that the increased number of sides introduces more complex structural and shielding requirements.

## 9.5 Wedge

The last shape that has been proposed is the wedge configuration. (Figure 1.14) This design is unique because the attachment points for the loads are placed on top of the elevator itself. The loads are placed in their own compartment; thus, providing shielding from space debris and extreme temperature changes. In addition to its rigid structure, the wedge shape can be easily mounted to the pallets inside the Space Shuttle cargo bay; thereby, making it easy to transport.

## Chapter 10. CONTROL STRATEGIES

The purpose of control strategies is to position the elevator at any desired location with respect to the tether, while simultaneously minimizing any vibrations that might occur in the elevator or on the tether. Computers on board the SS will interface with computers on board the elevator to control positioning functions.

### 10.1 Positioning

Horizontal positioning of the elevator is necessary to insure that the CM of the elevator is located on the tether. Unwanted vibrations could occur if the CM is offset from the tether. Sensors will be attached in various locations to determine moments about specific points on the elevator. This information will be sent to the CPU on board the SS, which will determine the location of the elevator's CM. Once the CM of the system has been found, a positioning mechanism will be used to move the elevator to the respective location.

## Chapter 11. HORIZONTAL POSITIONING GEOMETRIES

Since the drive mechanism must remain enclosed within the main unit, the subject of tether travel geometries must be investigated. These tether travel geometries will be located on the roof and floor of the main unit. They must allow the desired tether travel and keep the interior of the main unit enclosed. Five positioning geometries are

## *WEDGE CONFIGURATION*

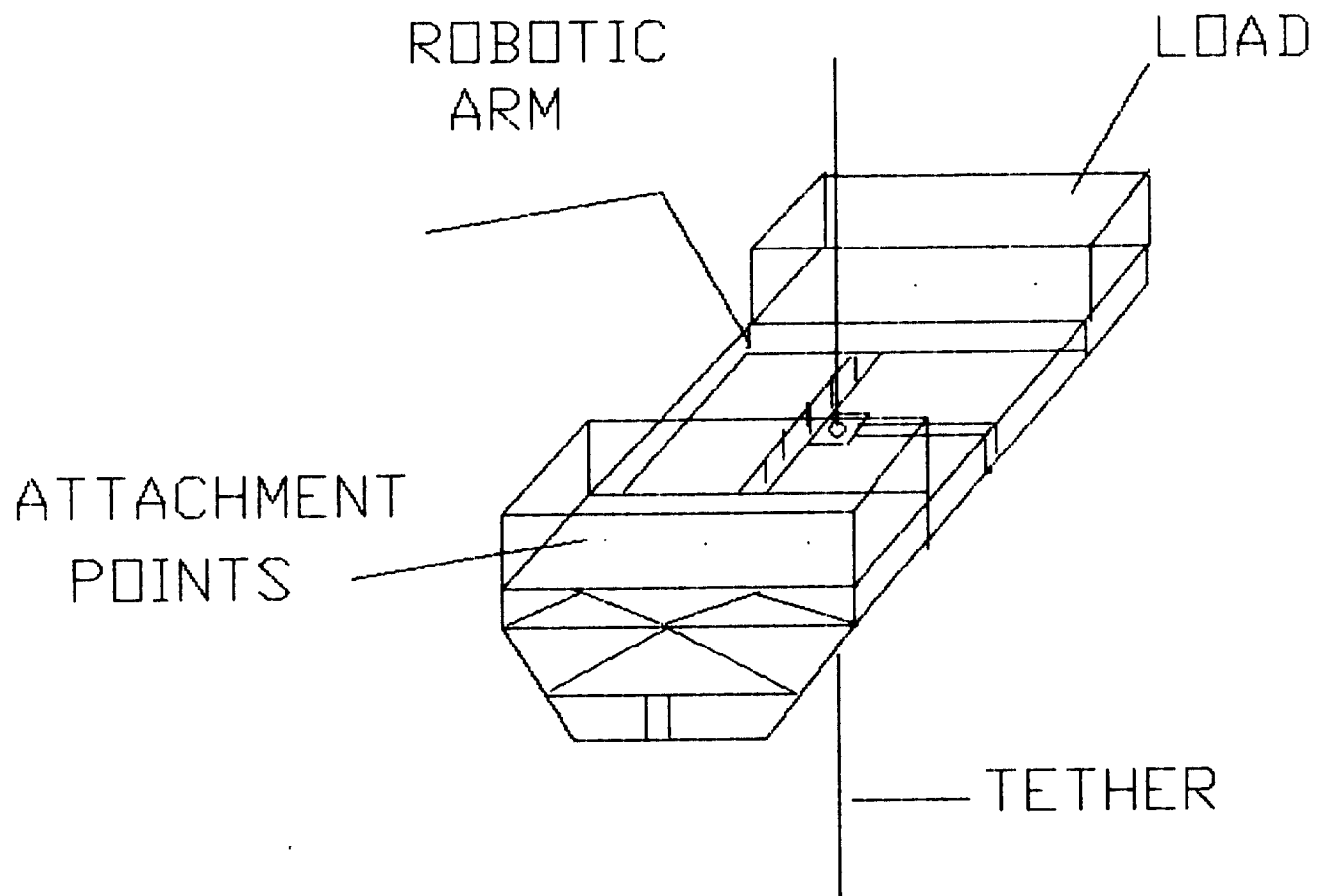


Figure 1.14

considered in this section, a hollow square, a sliding slot, a cross geometry, a rotating slot, and a stationary slot. The moment axis is the axis on which the pallets and/or various modules will be located.

#### 11.1 Hollow Square

The hollow square is simply a hollowed out area of the main unit in which the tether may travel. (Figure 1.15) It is the simplest of the proposed geometries, however it does not provide environmental protection for internal components of the main unit. It allows a large travel area, and would make access to the drive mechanism very easy.

#### 11.2 Sliding Slot

The sliding slot consists of a slot which will travel along the load axis. (Figure 1.16) The tether will travel along the normal axis within the slot. The drive mechanism is protected by a series of plates which slide over each other to insure that the internal area remains covered. This configuration provides substantial travel along the load axis and meets internal component protection requirements. A disadvantage of this system is the complexity of the sliding plate configuration.

#### 11.3 Cross Slots

The crossing geometry consists of a slot along the load and nonload axes in which the tether can travel. (Figure 1.17) These slots could be covered by small sliding plates like those of the rectangular slot. The major disadvantage of this geometry is the limited travel area of the tether.

#### 11.4 Rotating Slot

The rotating slot allows the tether to enter the slot where it is positioned by rotating the slot. (Figure 1.18) This geometry is relatively simple, with one disc as the only major moving part (not including gears to move the disc). It also provides a substantial tether travel area.

#### 11.5 Stationary Slot

Another option considered is the stationary slot geometry. This geometry is simple in structure and provides the protection needed to all internal components. The stationary slot, however, will only allow the elevator's CM

HOLLOW SQUARE GEOMETRY

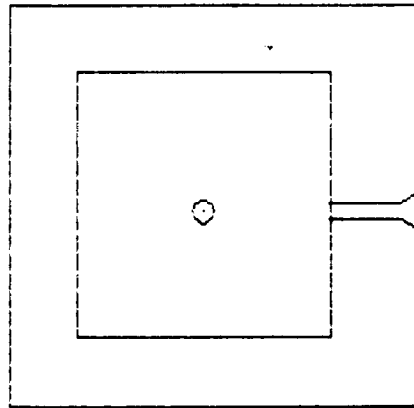


Figure 1.15

SLIDING SLOT GEOMETRY

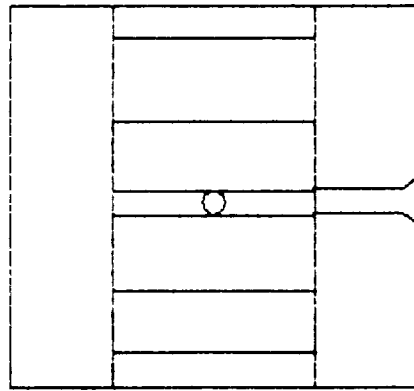


Figure 1.16

*ROTATING SLOT GEOMETRY*

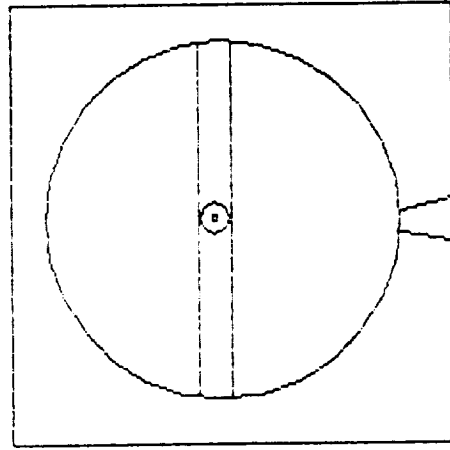


Figure 1.18

*CROSSING SLOTS GEOMETRY*

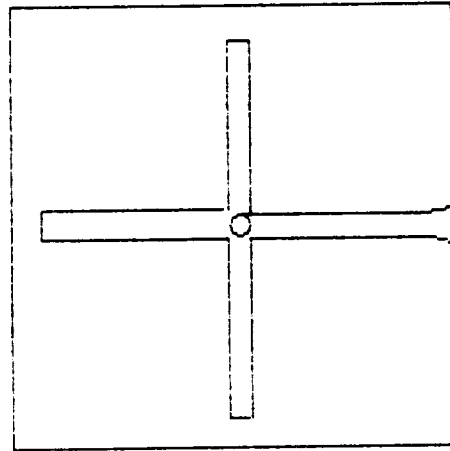


Figure 1.17

to be positioned perpendicular to the load axis. (Figure 1.19) For this reason it must work in conjunction with a counterbalance system which would allow CM positioning along the loaded axis. The stationary slot also allows for more internal volume usage within the elevator. In addition, it limits tether movement within the elevator, thereby, adding to the system's simplicity.

## Chapter 12. HORIZONTAL POSITIONING MECHANISMS

The horizontal positioning mechanism must connect the main unit to the drive mechanism in order for the system to be able to move relative to the tether. Next, four different positioning mechanisms will be introduced. Three of these configurations use worm gears to move the drive mechanism, while the other one uses a combination of worm gears and take-up reels.

### 12.1 Two Bar Worm Gear

The two bar worm gear is one of the simplest of the designs. (Figure 1.20) It consists of perpendicular worm gears which will allow movement in the horizontal plane. Sleeve gears will be attached to adjacent sides of the drive mechanism and will slide along the two worm gears. This will allow positioning of the drive mechanism virtually anywhere within the envelope of the main unit. An advantage of this system is its simplicity. Since the worm gears are the only interface between the main unit and the drive mechanism, they must also provide the strength required to support the main unit when the elevator traverses the tether. This will require that the worm gears be constructed of very strong material, and this could add extra weight to the system.

### 12.2 Three Bar Worm Gear

The second configuration presented is the three bar worm gear. (Figure 1.21) Its operation is similar to that of the two bar worm gear, however, two worm gears are used to travel along the normal axis. With this design the drive mechanism translates along the load axis worm gear. The load axis worm gear in turn, translates along the other two gears.

### 12.3 Parallel Worm Gear

The third positioning mechanism investigated is the parallel worm gear. (Figure 1.22) It provides positioning in only one direction, and could be used best with the stationary slot geometry. The parallel worm gear is the

## *STATIONARY SLOT GEOMETRY*

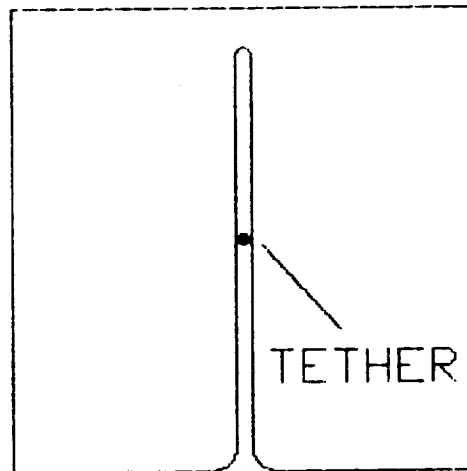


Figure 1.19



## *TWO BAR WORM GEAR POSITIONING MECHANISM*

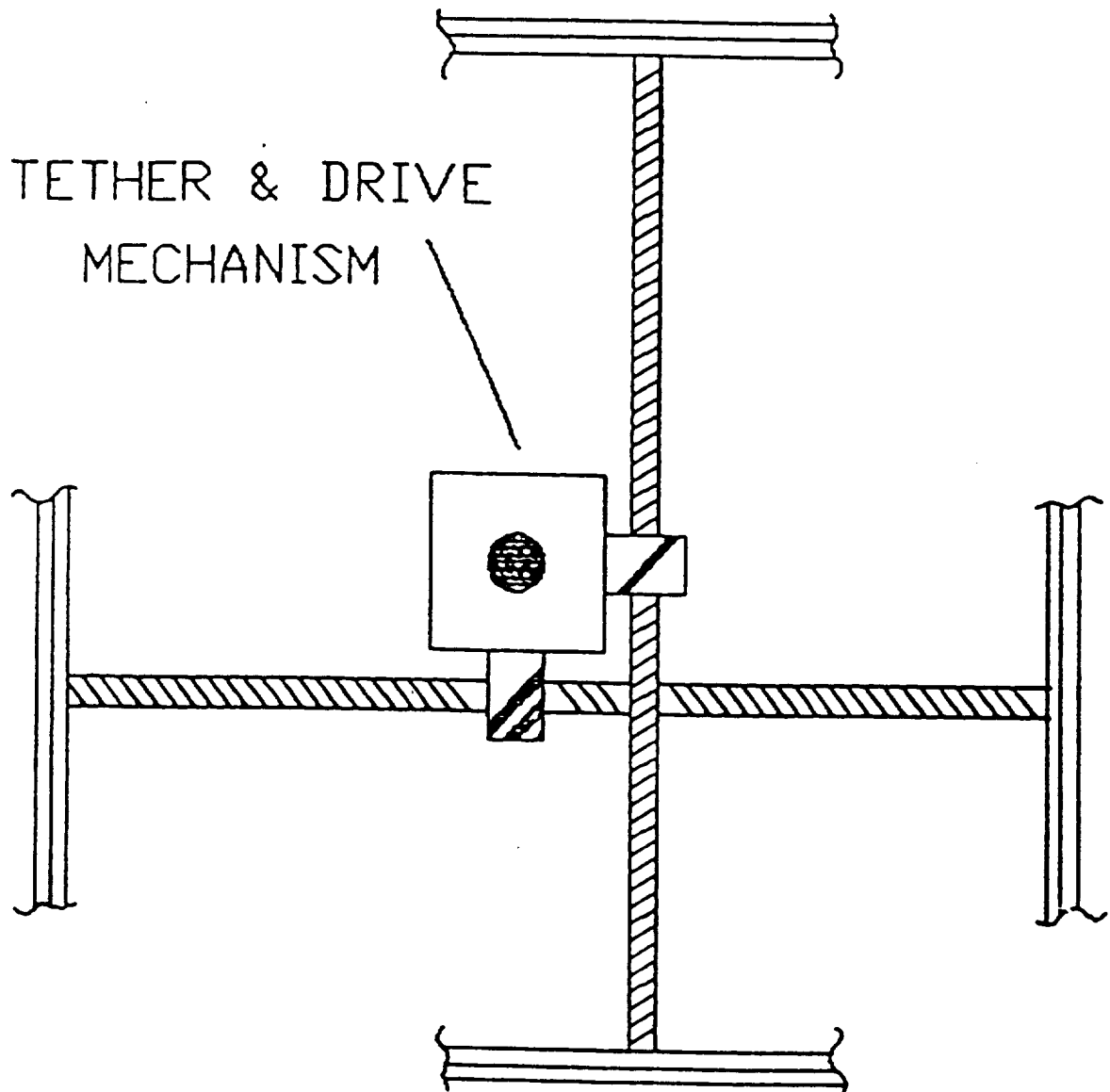


Figure 1.20

# THREE BAR WORM GEAR POSITIONING MECHANISM

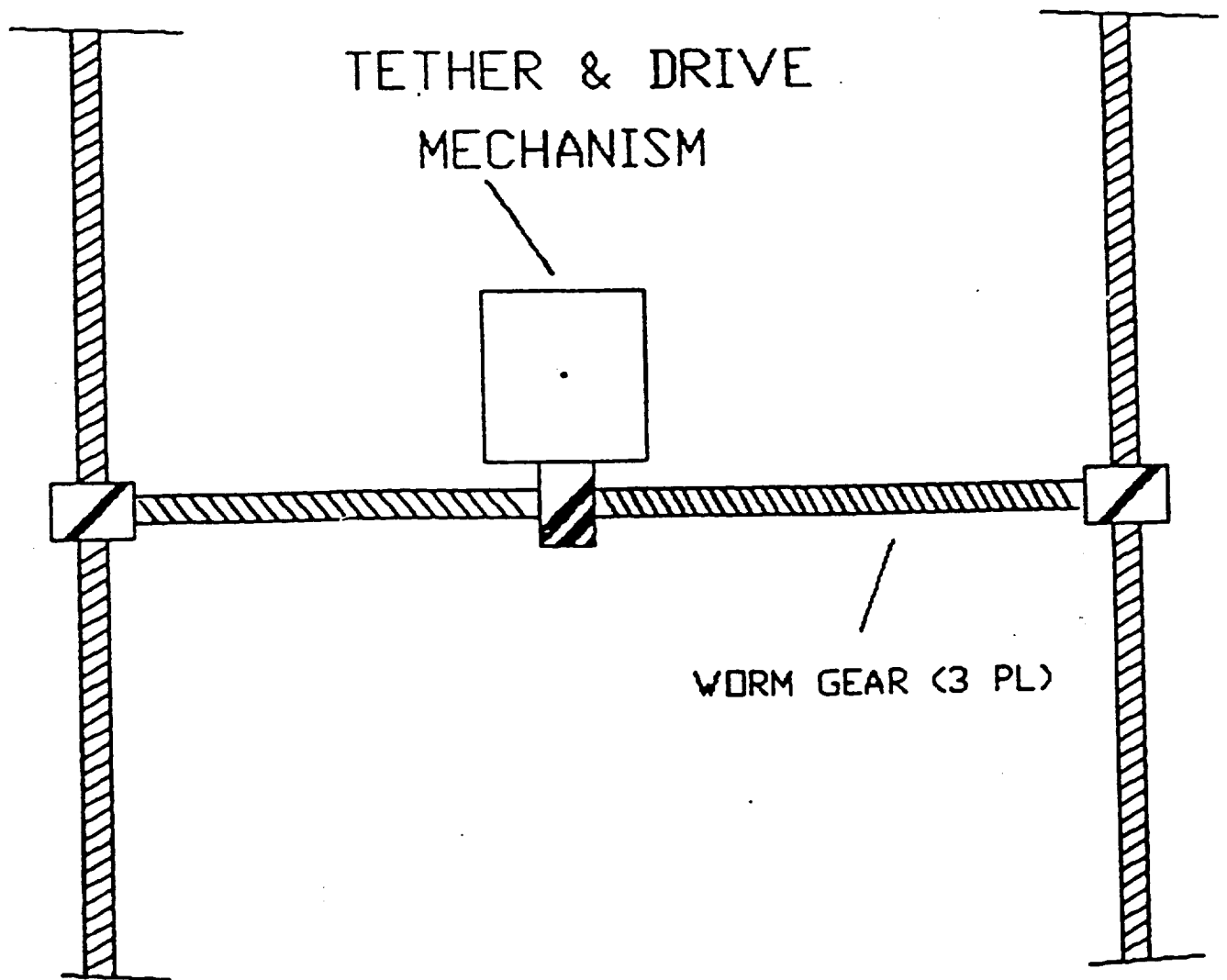


Figure 1.21

## *PARALLEL WORM GEARS POSITIONING MECHANISM*

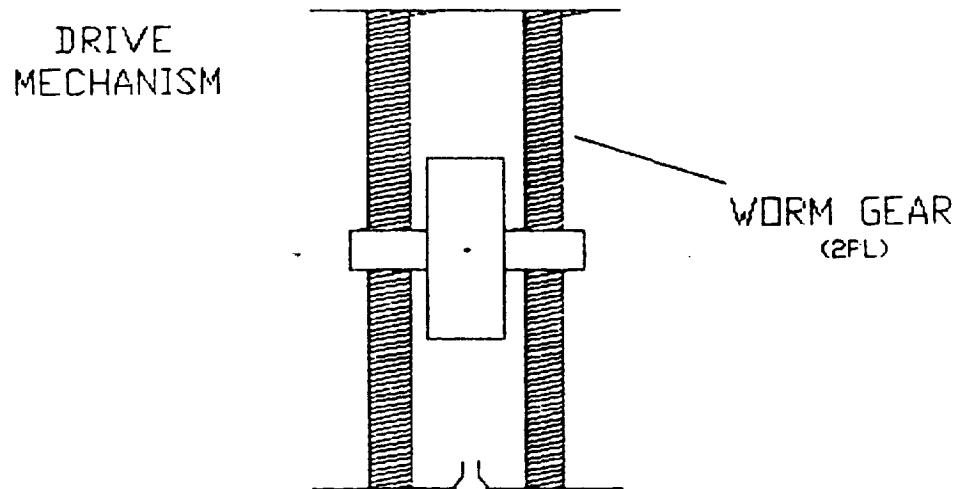


Figure 1.22

simplest and most structurally stable of all four alternatives.

#### 12.4 Two Bar / Two Reel Mechanism

The last configuration being considered is a two bar / two reel mechanism. (Figure 1.23) This mechanism uses a cable system, instead of worm gears, to move the drive mechanism along the load axis. The cables are controlled by two reels on either end which pull them back and fourth until the required CM of the elevator is obtained. In addition, the two reels ride on a track in order to create motion in the nonload axis. One advantage of the two bar / two reel mechanism is that the drive mechanism does not ride on worm gears, thus eliminating friction and actuator lubrication requirements. Also, all of the motion occurs inside the reels, which have their own casings. This separates the motor into a replaceable unit.

The horizontal positioning mechanism could be used primarily as a fine tuning instrument if an adjustable counterbalance is going to be used to make large moment adjustments.

### Chapter 13. COUNTERBALANCE MECHANISMS

Several configurations for the adjustable counterbalance are being considered:

- 1) Telescoping Strut
- 2) Scissors Mechanism
- 3) Worm Gear

The goal of each of the adjustable counterbalance configurations is essentially the same: to create large enough moments to insure that the CM is located on the tether. The difference in each type is the way the mass is moved outward from the elevator.

#### 13.1 Telescoping Strut

The first consideration is the telescoping strut design (Figure 1.24) The mass is adjusted in and out by a pair of telescoping struts on opposite sides of the elevator. One advantage of the system is its ability to move the attached mass outward to any desired position. Also, there has been previous design work already completed in this area which would eliminate time-consuming and costly research. One disadvantage of this design is storage requirements for the collapsed strut, which could interfere with the hardware housed inside the elevator.

*TWO BAR / TWO REEL  
POSITIONING MECHANISM*

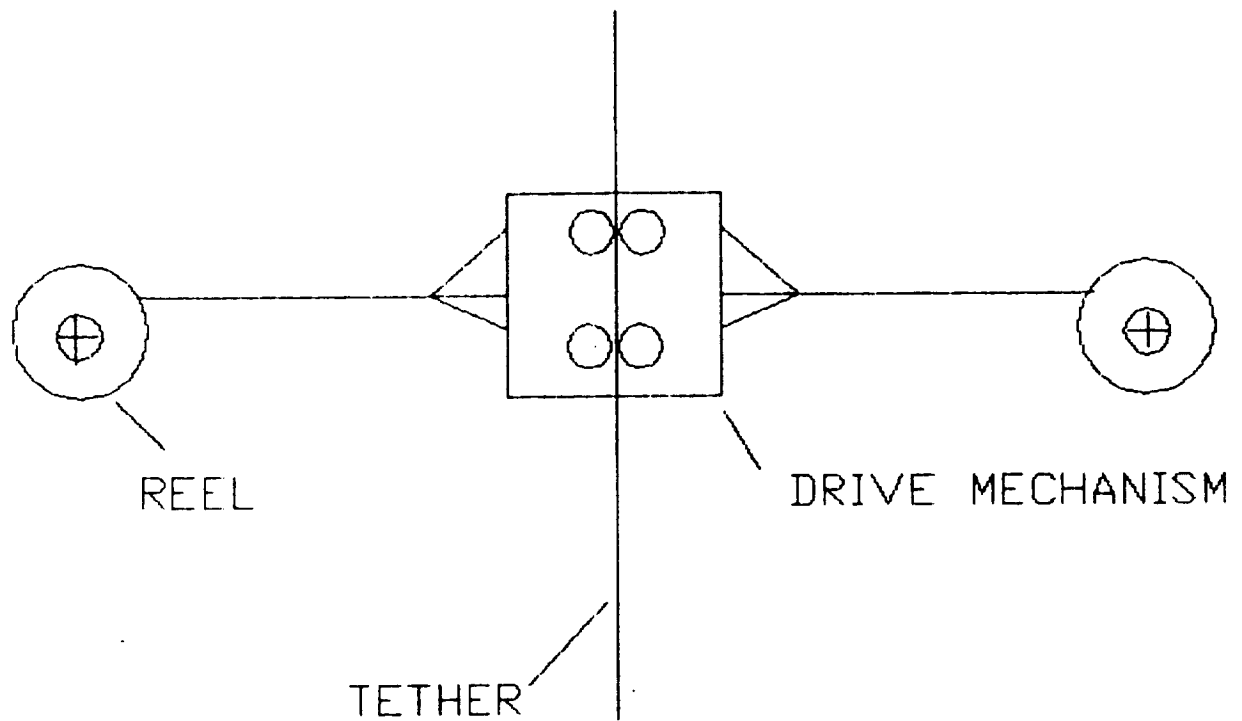


Figure 1.23

## TELESCOPING STRUTS COUNTERBALANCING MECHANISM

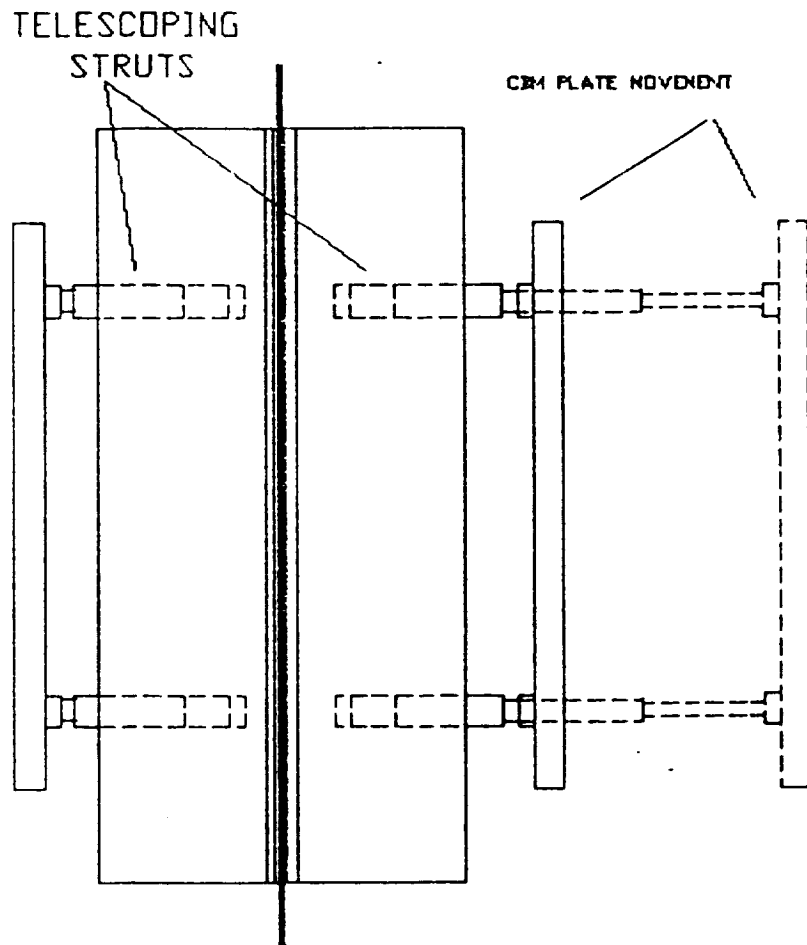


Figure 1.24

### 13.2 Scissors Mechanism

The second consideration is the scissors mechanism. (Figure 1.25) The mass will be positioned outward from the main unit using a scissoring mechanism. The advantage to this type of mechanism is its compactness. A disadvantage in this design is its lack of stability.

### 13.3 Worm Gears

The last type is the worm gear configuration. (Figure 1.26) Twin worm gears would move the mass in and out to the desired location. An advantage to this design is its simplicity. A disadvantage, however, would be the limited travel of the worm gear in positioning the mass outward from the elevator. The distance would be limited to the width of the elevator. Another disadvantage of this design is its interference with tether hook/unhook when the worm gears are stowed.

Vertical positioning is not a main concern of this group's design. It will be accomplished through use of the drive mechanism, which is addressed in Section III. However, positioning is a factor which must be considered when calculating tether tension with respect to elevator position on the tether. The exact position of the elevator can be determined by counting the revolutions of the drive belt and using the circumference to determine the distance traveled from the SS or end mass.

## Chapter 14. ELEVATOR CONFIGURATION OPTIMAL SOLUTION - DESIGN PHASE II.

In order to select an optimal solution for the design of the TECTS, all mechanisms and configurations were evaluated using a decision matrix. (Appendix B) The matrix obtains an optimal solution by comparing all of the alternatives over a wide range of design parameters. The design parameters selected are those that are felt to be most pertinent to that particular mechanism or configuration. Each of these parameters is then assigned a weighing factor ranging from zero to ten with the largest being the most significant. This is used to relate the different parameters to each other. Each alternative is then assigned a number between zero and twenty for each design parameter, with the largest number being the most favorable. A summation of the most favorable number multiplied by the weighing factor is then performed for each of the alternatives. This gives a numerical representation of the rating of each design. When these are compared the higher value becomes the most favorable, and is the optimal solution.

## *SCISSORS COUNTERBALANCING MECHANISM*

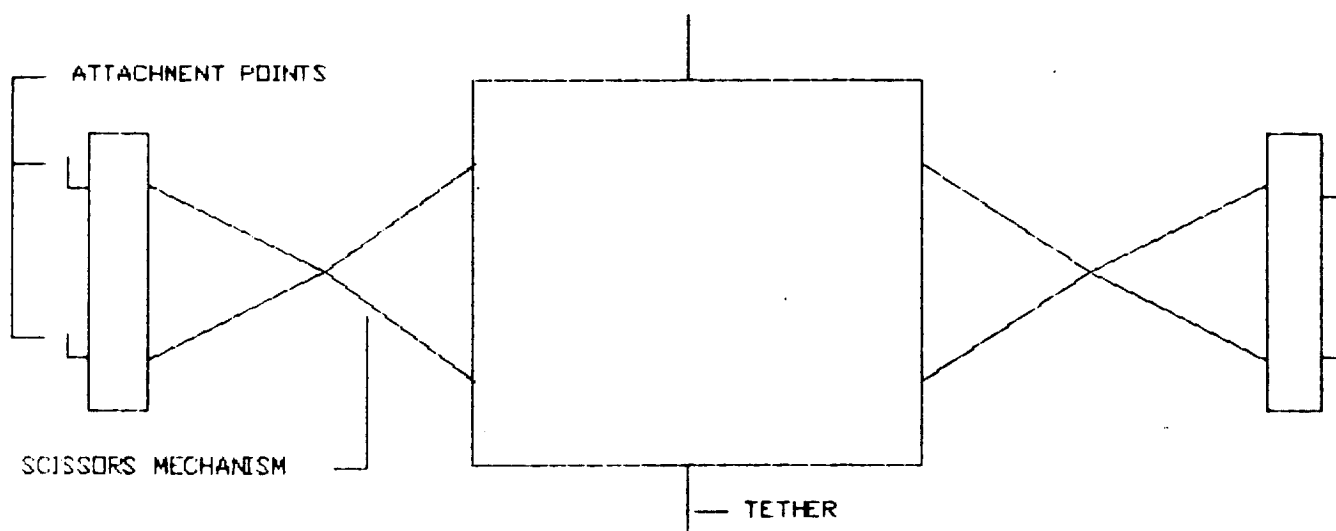


Figure 1.25



## *WORM GEAR COUNTERBALANCING MECHANISM*

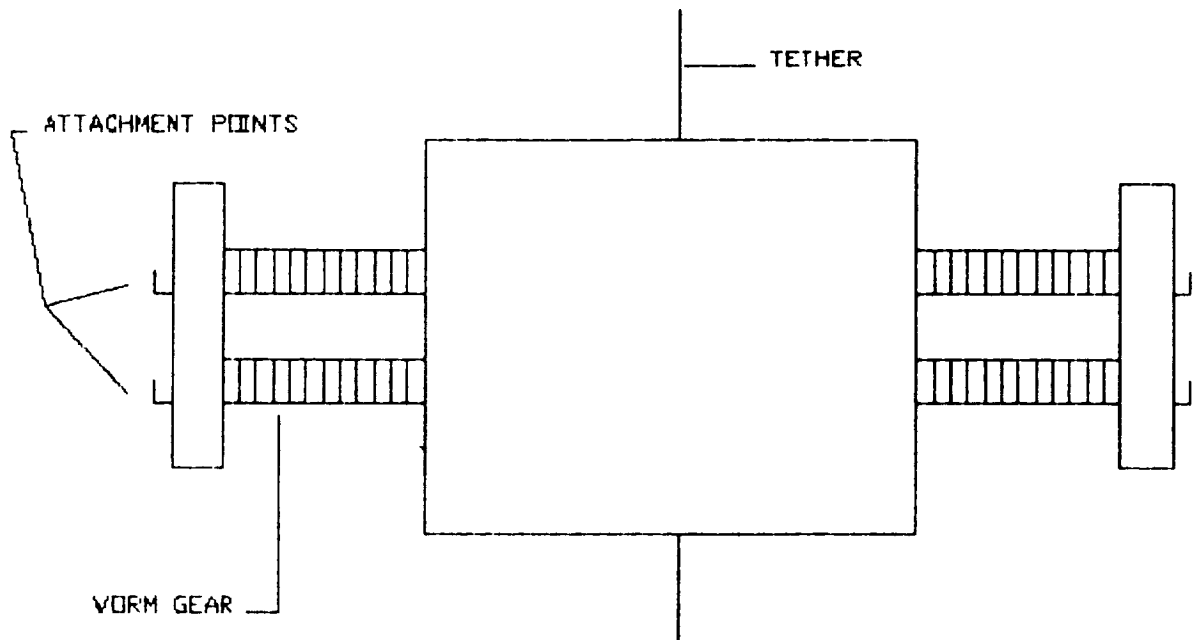


Figure 1.26

This procedure was performed for each of the elevator component designs. The optimal solution from each was then combined to give a configuration for an elevator. This configuration was then compared against the modified Component and modified Dual Pallet designs from Design Phase I.

The parameters used in the decision matrices of this paper can have many meanings. However, each one will be defined specifically for purposes of this report. A list of the definitions is provided in Appendix C.

#### 14.1 Main Unit Shapes

The shapes, shown in Figures 1.10 through 1.13, are all top views of the Main Unit. They all have advantages and disadvantages, however, the octagon has been determined to be the optimal design for the TECTS. (See Solution Matrix 1.2) The chamfered corners provide the octagon with better structural stability as well as the lowest stress concentration areas. Another advantage includes high internal storage capacity, which is needed for the spherical power system fuel tanks. Its extra sides provide more access panel areas and easier EVA capabilities.

The octagon is compatible with all proposed positioning geometries and mechanisms, as well as, the counterbalance mechanisms.

#### 14.2 Horizontal Positioning Geometries

The positioning geometries are the cross sectional views of the top and bottom of the elevator. Their main purpose is to protect all internal components, as well as, to allow for tether travel when positioning the elevator's CM by means of positioning mechanisms. The geometries considered in the decision matrix are as follows:

- \* Hollow Square
- \* Stationary Slot
- \* Sliding slot
- \* Cross geometry
- \* Rotating slot

The optimal positioning geometry (See Solution Matrix 1.3) selected in the decision matrix was the stationary slot. (Figure 1.19) The major parameters that contributed to the decision were simplicity, internal protection, internal volume storage, and hook/unhook capabilities. The stationary slot was second to the hollow square in simplicity. However, the hollow square was not

considered since it did not provide protection to all internal components. This parameter is crucial since protection from space debris and temperature fluctuations must be provided during normal space operations. The stationary slot satisfied this parameter well.

Besides simplicity, the stationary slot provides the elevator with maximum internal volume usage. Internal volume is also a crucial parameter, since enough volume is needed to house all components, such as power systems and drive mechanisms. Furthermore, the stationary slot is favored since it allows easy hook/unhook capabilities. The slotted track within the geometry will simply provide support and guidance in the hook/unhook process, thus increasing the reliability and the performance of the elevator.

#### 14.3 Horizontal Positioning Mechanisms

The term horizontal positioning mechanism refers to the internal device used to adjust the position of the CM. The suggested positioning mechanisms are the two bar worm gear, three bar worm gear, parallel worm gear, and the two bar-two reel. After an analysis using an optimization matrix (See Solution Matrix 1.4) it was determined that the parallel worm gear is the optimal solution.

The parallel worm gear is the simplest of the four designs. It has fewer moving parts and will be easier to manufacture. This mechanism does not provide as much stability to the structure of the elevator as its competitors, however, due to the limited amount of parts required there is less mass added to the system. With less mass involved, a smaller amount of internal volume will be required to house this component.

A disadvantage of the parallel worm gear mechanism is that its movement is limited to one direction. All of the other mechanisms are able to move in a two dimensional plane. Vibrations delivered to the tether from the motion of the positioning mechanism are concerns. According to the matrix analysis it was determined that the parallel worm gear would provide the smallest contribution.

The parallel worm gear will be able to carry loads equal to that of the two bar worm gear mechanism. Both of these mechanisms have two gear tracks supporting the load, so that half of the total load is carried by each of the gear tracks. However, the three bar worm gear only has one bar spanning the elevator. This means that the entire load must be supported by a single worm gear.

After computing the solution optimization matrix the

parallel worm gear and the two bar worm gear had close weighted averages. The main problem with the two bar worm gear is that it requires guide tracks on all sides of the elevator. This severely restricts the possibility of having an opening to let the tether enter during hook/unhook procedures.

#### 14.4 Counterbalance Mechanism

After close consideration of the three pending designs, the telescoping strut was chosen as the optimal design. The optimization matrix shows how this decision was made. (See Solution Matrix 1.5) The matrix proves clearly that the scissoring mechanism is inferior in almost every area. However, it also shows how very closely the telescoping strut and the worm gear designs are matched. Either of these two designs could have been chosen, but the following discussion details why the telescoping strut design was chosen.

When examining the matrix for areas that the telescoping strut is weighed heavier than the worm gear, it is noted that the worm gear nearly equals the telescoping strut. However, it does not equal the telescoping strut in total number. Simplicity and hook/unhook are the influencing parameters. The telescoping strut is simpler in design and will require less internal volume. It is also seen to be better for the hook/unhook procedure because there will be less chance of interference.

Another important factor in deciding to select the telescoping strut design was the amount of research already completed in this area. With the use of Carbon Fibre Reinforced Plastics a combination of high strength, stiffness and low mass can be obtained.[8] An Extendable and Retractable Telescopic Mast (ERM) (currently under development) is available in a circular or square shape design. With a minimum number of tube-sections the stowed size can be minimized. Potential sizes available have deployed lengths of 6m to 40m with stowed lengths of 1.5m and 3.3m.[8]

### Chapter 15. SYSTEMS ELEVATOR DISCUSSION

The optimal designs that will be incorporated into the Systems Elevator will be as follows: the octagon shape, the parallel worm gears, the stationary slot for tether travel, and the telescoping struts.

# OPTIMIZED SYSTEMS ELEVATOR

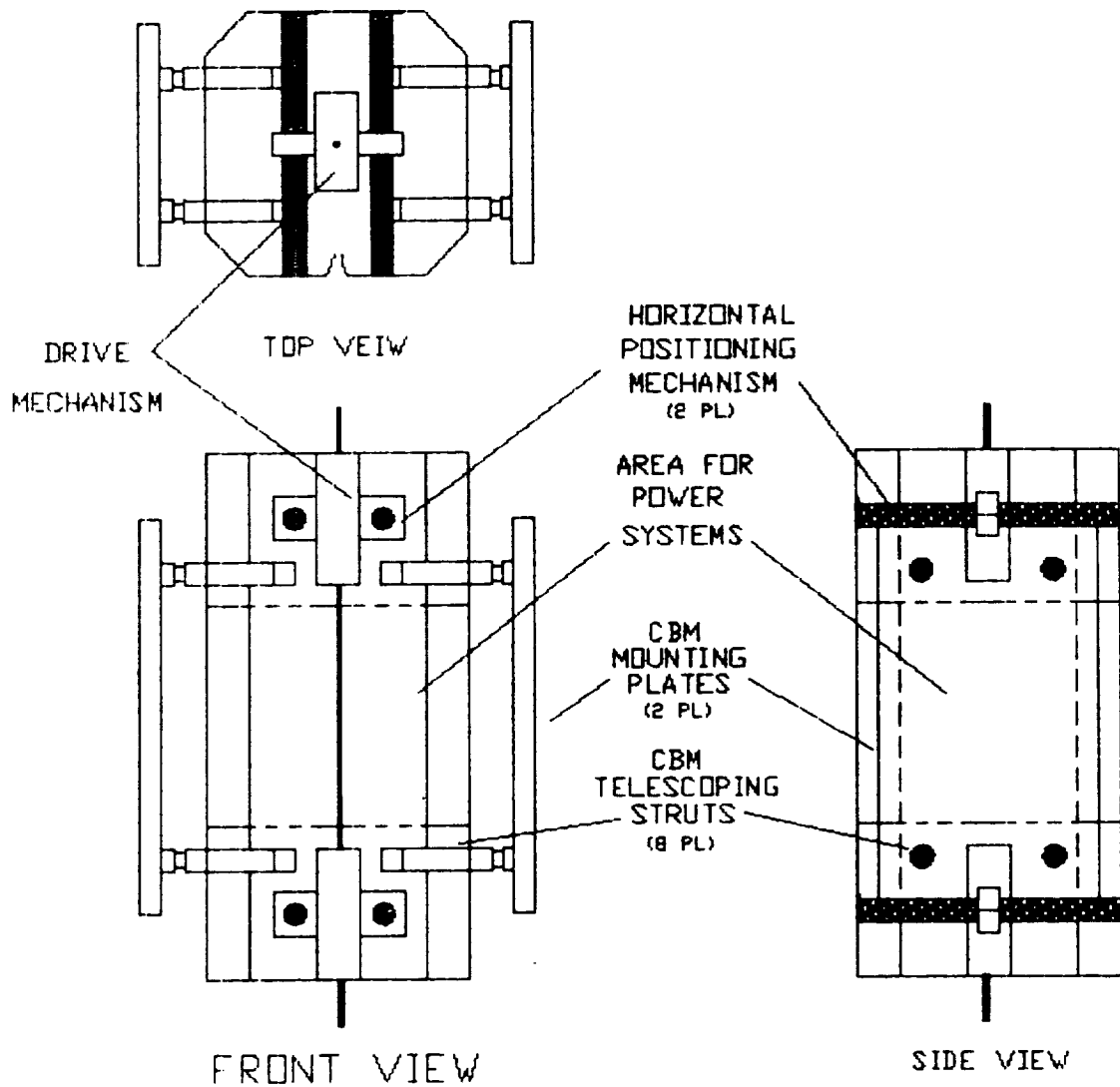
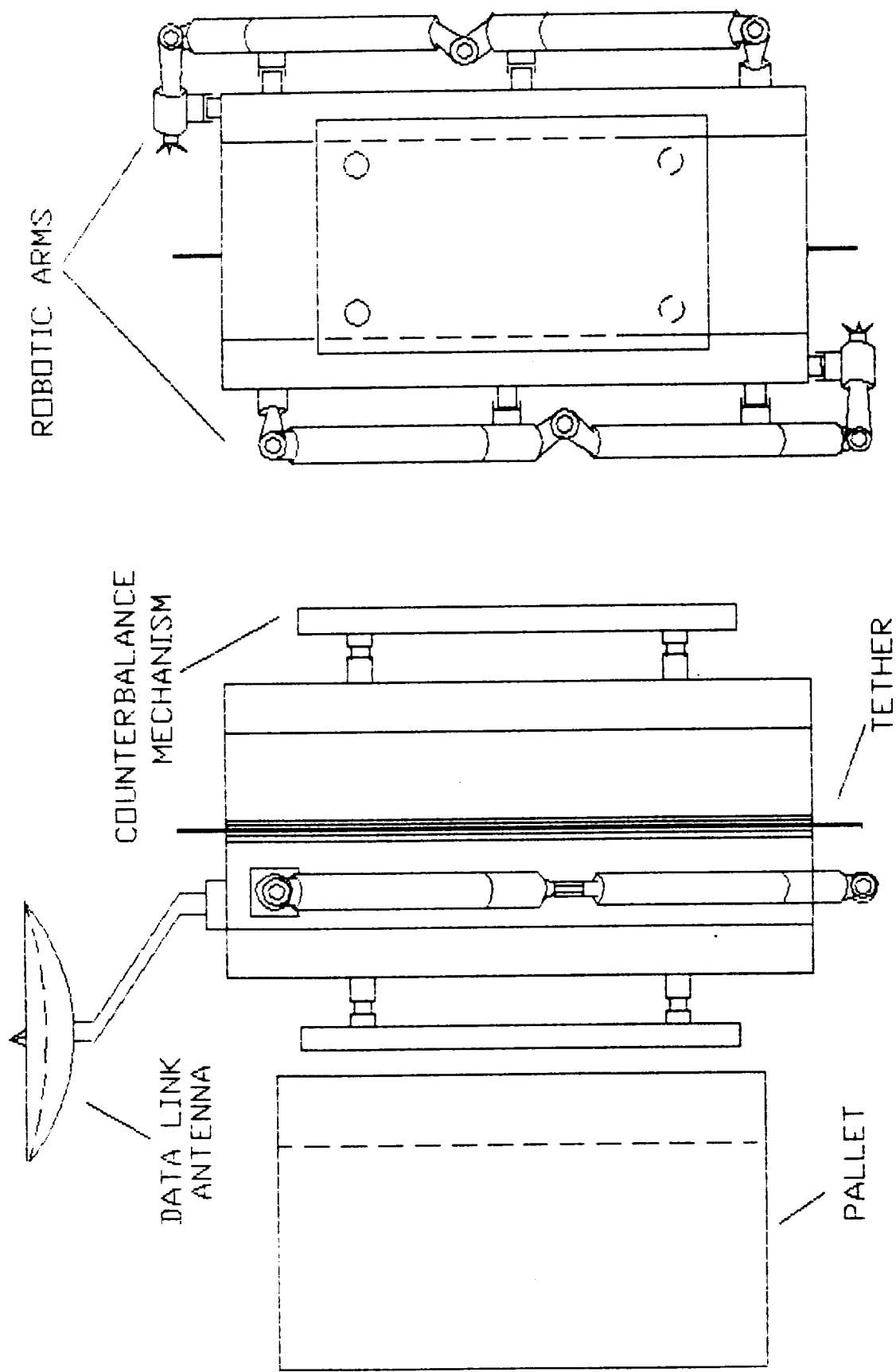


Figure 1.27



**EXTERNAL COMPONENTS  
(OPTIMIZED ELEVATOR)**

Figure 1.28

## ACCESS PANEL LOCATION (OPTIMIZED ELEVATOR)

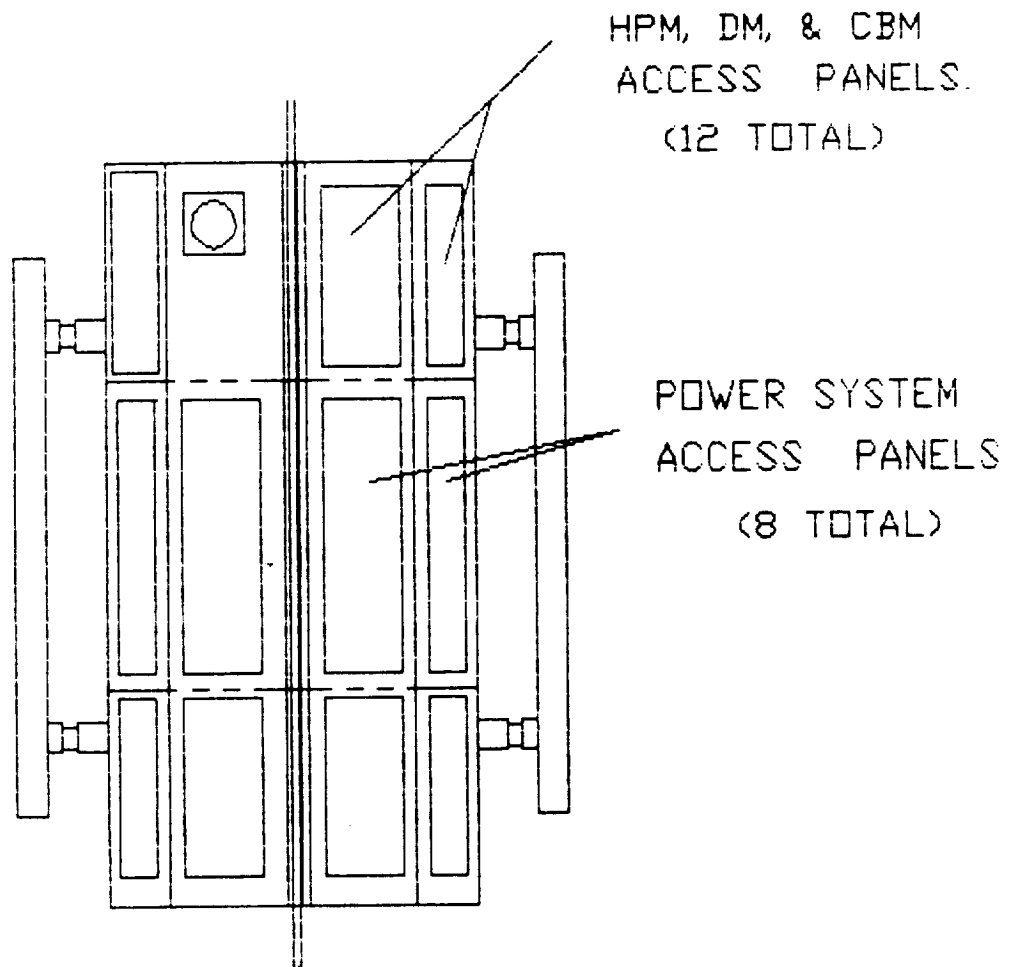
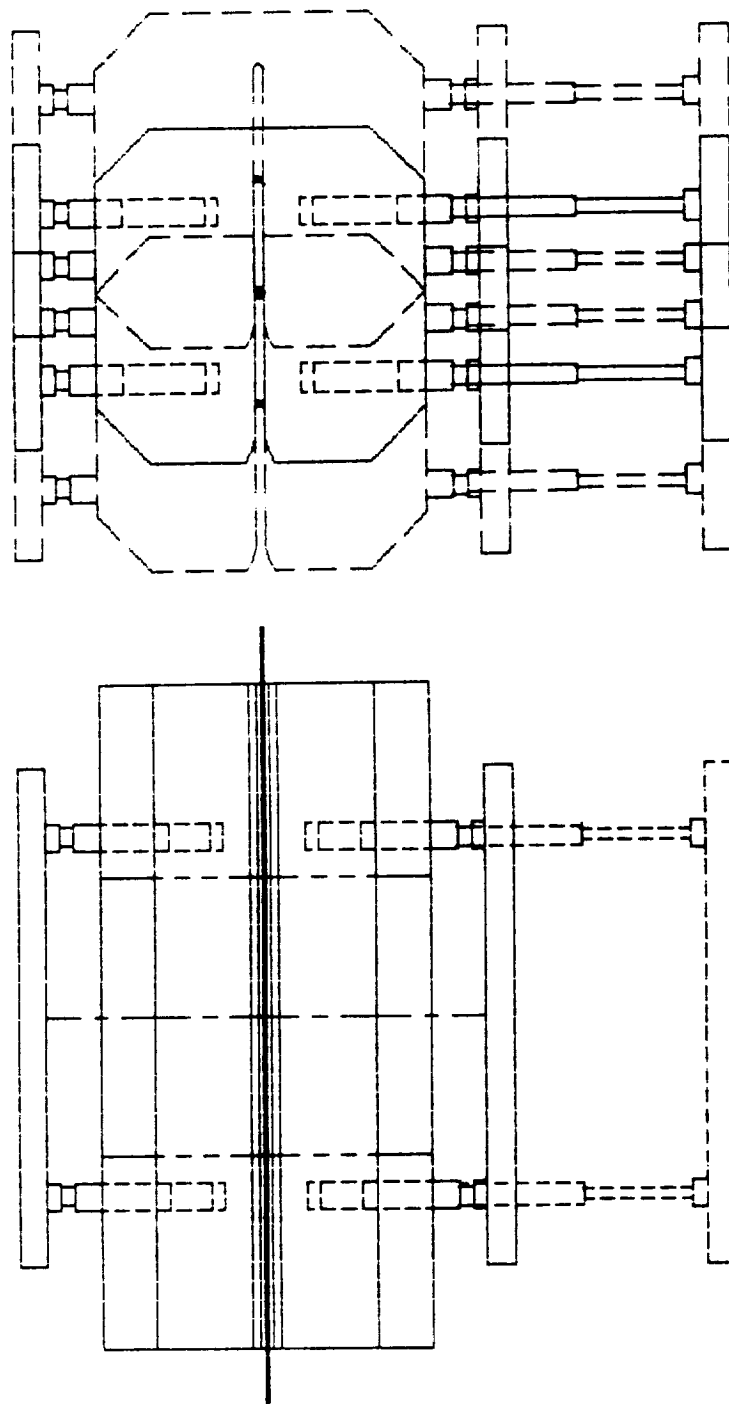


Figure 1.29



*CM MANAGEMENT SYSTEM  
(OPTIMIZED ELEVATOR)*

Figure 1.30



## 15.1 System Locations

The location of each of these systems is shown in Figure 1.27. The elevator has been divided into three different compartment sections. The drive and positioning mechanisms are located at both ends of the elevator in a 2.5 foot envelope. This configuration provides a five foot distance along the center of the octagon's length for locating the power system.

The location of each external component is shown in Figure 1.28. Since the SS is located above the elevator, the data link antenna is attached on the top of the elevator to aid in transmission. The robotic arm is located (when stowed) to prevent interference with tether hook/unhook operations. Finally, the pallets will be attached vertically on the counterbalance mechanism plates to help stabilize the system.

## 15.2 Access Panels

In order for maintenance operations to be performed on the system, it is necessary to install access panels. Figure 1.29 shows possible locations for removable panels which would allow access to all of the required systems. This configuration provides six access panels at the top and bottom of the elevator. These panels provide access to drive, horizontal positioning, and counterbalance mechanisms. Eight access panels, four on the front and four on the back, are also provided for access to the power system.

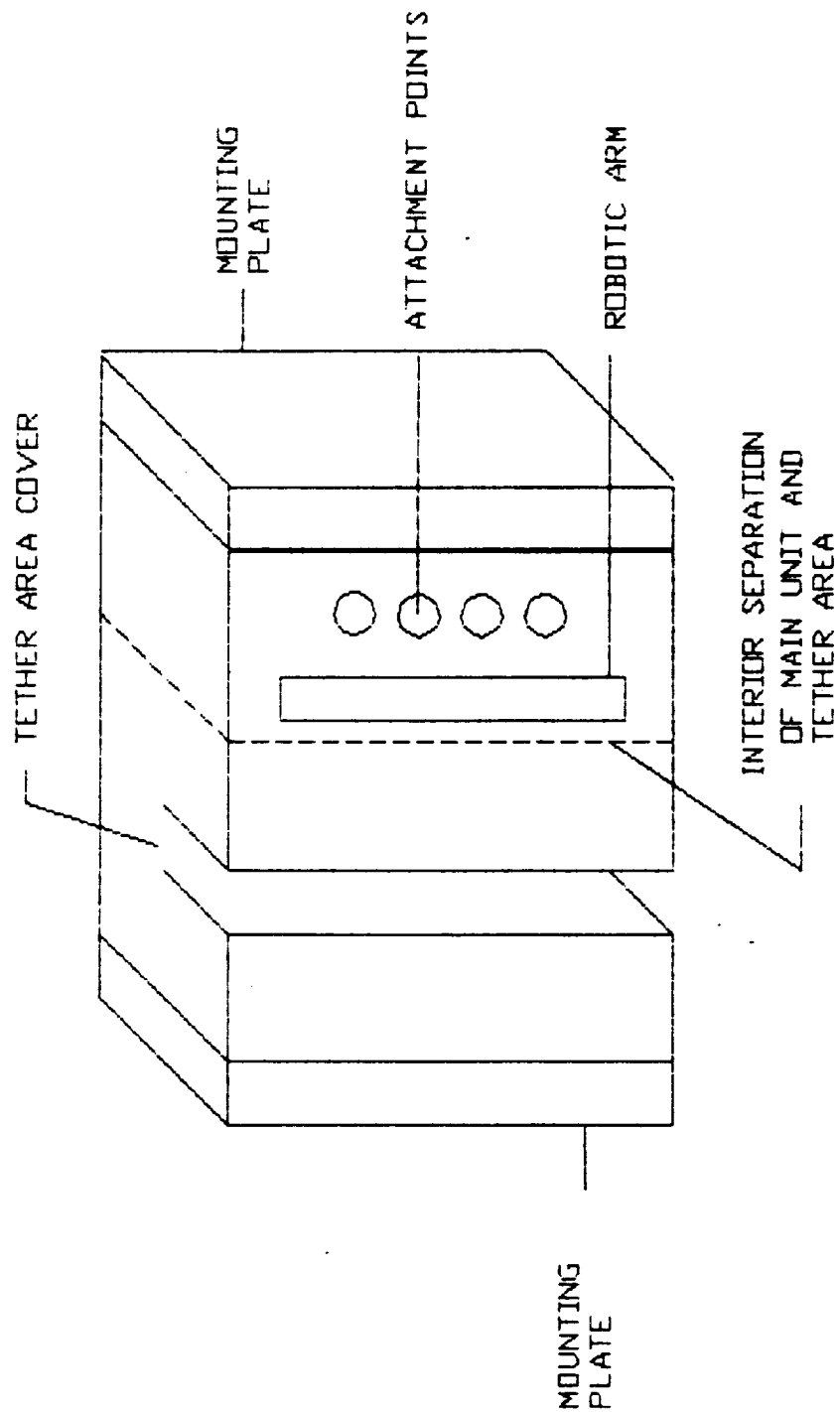
## 15.3 CM Management Capabilities

The CM management system provides for system movement in four directions. (Figure 1.30) The elevator can be moved four feet along the stationary slot. Also, the counterbalance mechanism can move the mounting plates up to fifteen feet away from the main unit.

## Chapter 16. OPTIMAL ELEVATOR DESIGN

The Systems Elevator design has a horizontal positioning mechanism similar to that of the modified Dual Pallet. (See Figure 1.31) However, it also has the advantage of telescoping struts. This allows positioning of the cargo as a means of moment elimination. In order for the modified Dual Pallet to eliminate these same moments, a two-dimensional positioning mechanism would be required. This is a very limited approach that was ruled out during the solution optimization phase.

## MODIFICATION OF DUAL PALLET ELEVATOR



## MODIFICATION OF DUAL PALLET ELEVATOR

Figure 1.31

The Systems Elevator design also has the advantage of being taller than the modified Dual Pallet configuration. This adds to the stability of the system.

The modified Dual Pallet Elevator does have one advantage over the Systems Elevator configuration: all the components are separated from the drive mechanisms. However, since this induces a moment on the elevator even when it is unloaded, this advantage is self-defeating.

Another disadvantage of the modified Dual Pallet design is that it is a rectangle, while the Systems Elevator design is an octagon. The octagon was determined to be the optimal shape using a solution optimization matrix. (See Solution Matrix 1.6) As a whole, the Systems Elevator design displays many advantages over the modified Dual Pallet elevator design.

## SECTION II.

### TETHERED ELEVATOR REMOTE MANIPULATOR SYSTEM

#### DESIGN PHASE I.

- \* Mechanical Elevator Interface
- \* Electrical Elevator Interface
- \* End Effectors
- \* End Effector Arm Tools
- \* Gripper End Effector Tools
- \* Control Systems
- \* Man-Machine Interfaces
- \* Arm Drive Mechanism

#### DESIGN PHASE II.

- \* Computer Hardware Systems
- \* Data Transfer Devices
- \* Control System Sensors
- \* Libration Minimization

## SECTION II. TETHERED ELEVATOR REMOTE MANIPULATOR SYSTEM

### INTRODUCTION

Many of the elevator functions will be performed or assisted by a remote manipulator arm mounted to the elevator. The manipulator will provide a mechanical linkage between the tether elevator and the end mass. End effectors on the manipulator will provide a means of securing or servicing many types of devices.

The purpose of this section is to conceptually design the manipulator for the elevator. In doing so, the utility of the tether has been explored in an attempt to define the requirements and capabilities expected of the arm. Many of the uses of the tethered elevator either depend entirely upon a remote manipulator arm attached to the elevator or are enhanced by the arm.

A long tether greatly extends the reach of the Space Station to objects in space with minimal expenditure of energy. With improvements in robotic technology, it is expected that the tether will eventually be used to exchange materials or fuels between the Space Station and the Orbiter, and retrieve payloads from the cargo bay of the Orbiter allowing the Orbiter to remain in a lower orbit.

Manipulators, in use and under development, have been studied to gain insight into the design of a manipulator for space applications and to better define the operations that can reasonably be performed by the manipulator on the elevator.

The Shuttle RMS is one of the most well know manipulators that has been used in space. It is a 15.3 m long, three jointed arm possessing six degree of freedom motion. The arm performs in space while anchored to the Orbiter. The standard end effector attaches to the wrist of the manipulator and is used primarily for grappling and releasing payloads and for applying loads and/or motion to the payload.[11] The capture mechanism is comprised of three cables that close around the grapple fixture.[11] The manipulator arm, when equipped with a standard end effector, is capable of capturing a payload with a large misalignment and is dexterous enough to position the payload relative to the Orbiter axis with precision.[12] The arm can maneuver a 665 kg payload with a maximum speed of 0.66 meters per second.[12] The SRMS is designed to operate in the micro-gravity environment of space. It is capable of transporting a Greyhound bus in space, but it cannot even support its own weight on earth.

A manipulator currently under development for use on the OMV will utilize technologies that may be required for or may enhance the operation of TERMS. With advances in robotic technology, the OMV is expected to meet one of NASA's near-term goals that of servicing spacecraft. In accomplishing this task, the manipulator on the OMV must be capable of operating mechanical and electrical connections, as well as devices for latching, cutting, and welding. It also must grasp and position objects and grapple docking fixtures or handholds.[13]

## DESIGN PHASE I. TETHERED ELEVATOR REMOTE MANIPULATOR SYSTEM

In order to converge upon a final solution for the manipulator system, the following subsystems will be investigated:

1. Mechanical Elevator Interface
2. Electrical Elevator Interface
3. End Effectors
4. Arm End Effector Tools
5. Gripper End Effector Tools
6. Control Systems
7. Man-Machine Interface
8. Arm Drive Mechanism

### Chapter 17. Mechanical Elevator Interface

The mechanical elevator interface can either be a fixed mount or a drive track. The fixed mount can be further subdivided into both permanent and interchangeable attachments. A permanent mount, via bolts, welds, and/or adhesives, would have the advantage of being simple, inexpensive, easily redundant and reliable.

Figure 2.1 shows a fixed mount RMS system. An interchangeable attachment such as a standard grapple fixture, expandable insert, self locking gripper, etc., would allow the RMS to be easily removed for servicing. This would allow it to be interchangeable with other compatible Space Station robotic systems, and to be removed when the elevator does not need robotic abilities. It would enable one arm to be used many places and be easily interchangeable for repair or replacement.

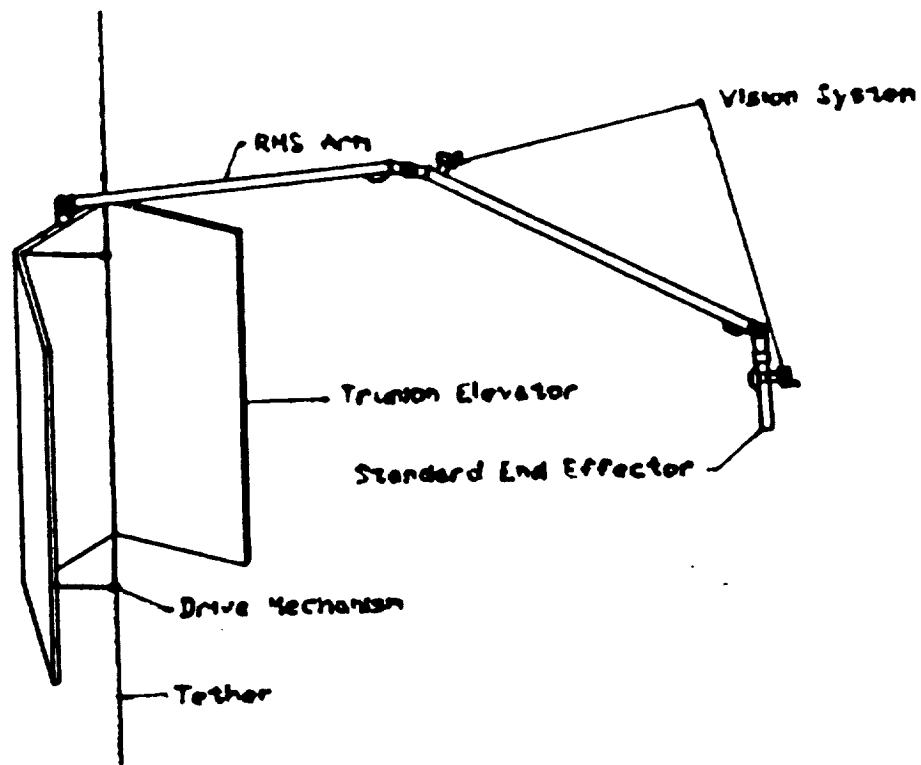
A track drive interface as shown in Figure 2.2, would enable the RMS to traverse the elevator. The greater mobility of the RMS would allow for greater flexibility.

### Chapter 18. Electrical Elevator Interface

Electrical communication and data relay connections between the elevator and the RMS will be accomplished via a connector. The two design considerations are a multipin connector and a coaxial cone connector.

The multipin connector as shown in Figure 2.3 is presently used as the electrical connection between the Shuttle RMS and an end effector tool. The coaxial cone connection as shown in Figure 2.4 is proposed as a connection that would allow for misalignments.

## PALLET ELEVATOR WITH STANDARD RMS



ORIGINAL FILE IS  
OF POOR QUALITY

Figure 2.1



# BARREL ELEVATOR WITH STANDARD RMS

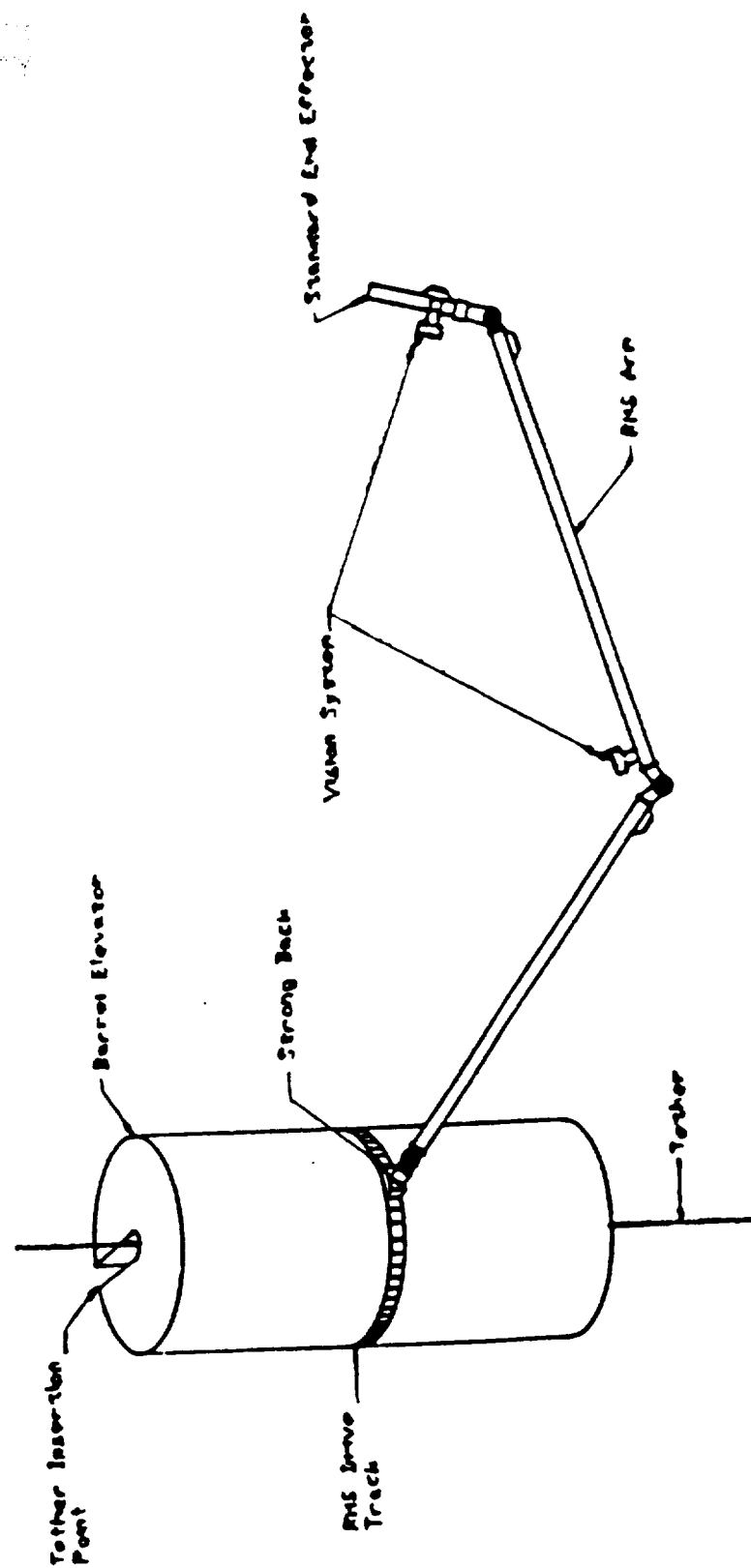


Figure 2.2

## STANDARD GRAPPLE FIXTURE

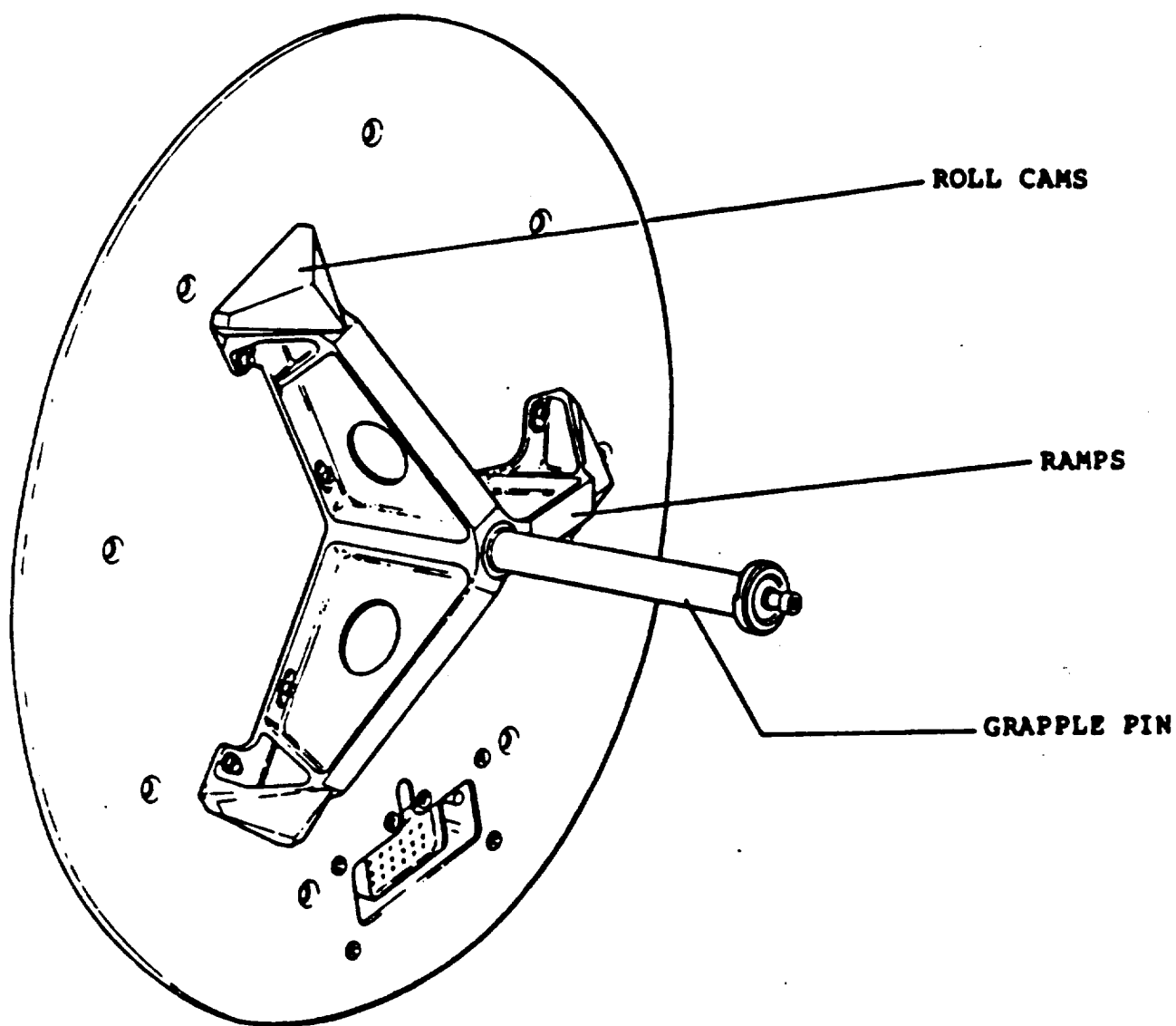
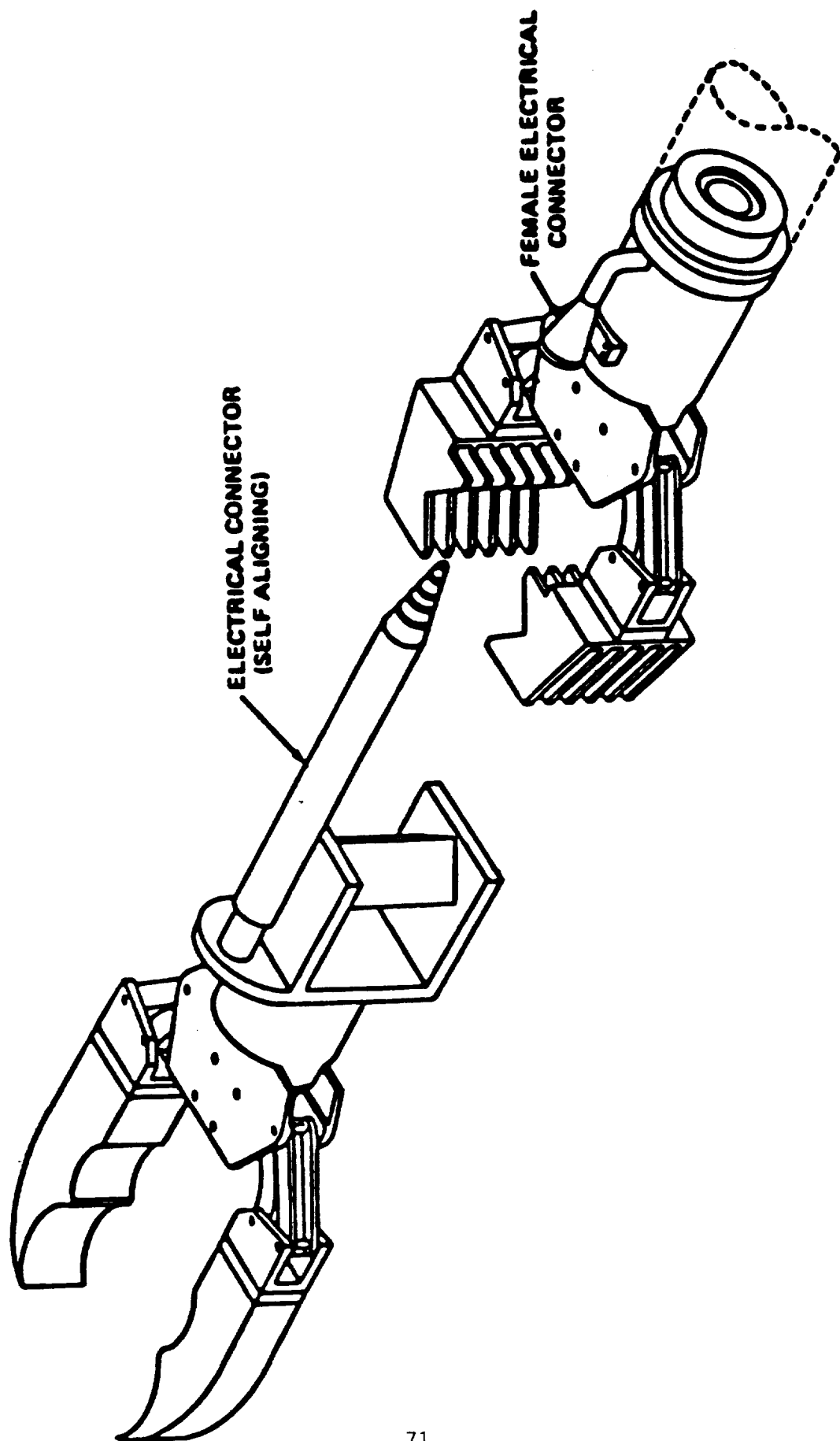


Figure 2.3



COAXIAL CONE ELECTRICAL CONNECTION

Figure 2.4

## Chapter 19. End Effectors

The RMS arm basic configuration has already been optimized by NASA and possesses capabilities which are more than adequate for TERMS. A variety of end effectors and end effector tools will be utilized to expand the dexterity and flexibility of the manipulator. The distinction between an end effector and an end effector tool is that an end effector is semi-permanently attached to the RMS arm while the end effector tool is not. Many end effector tools will be incorporated into the TERMS system, however, only one end effector will be used.

Six end effectors are being considered. They include the Standard End Effector (SEE), JPL Gripper, Langley Intelligent, JPL Prototype, 3 Finger Multijoint, and 3 Multijointed Finger. Each end effector is pictured in Figures 2.5-2.10.

The Standard End Effector is presently used on the SRMS. The remaining five end effectors are under development at various NASA centers.

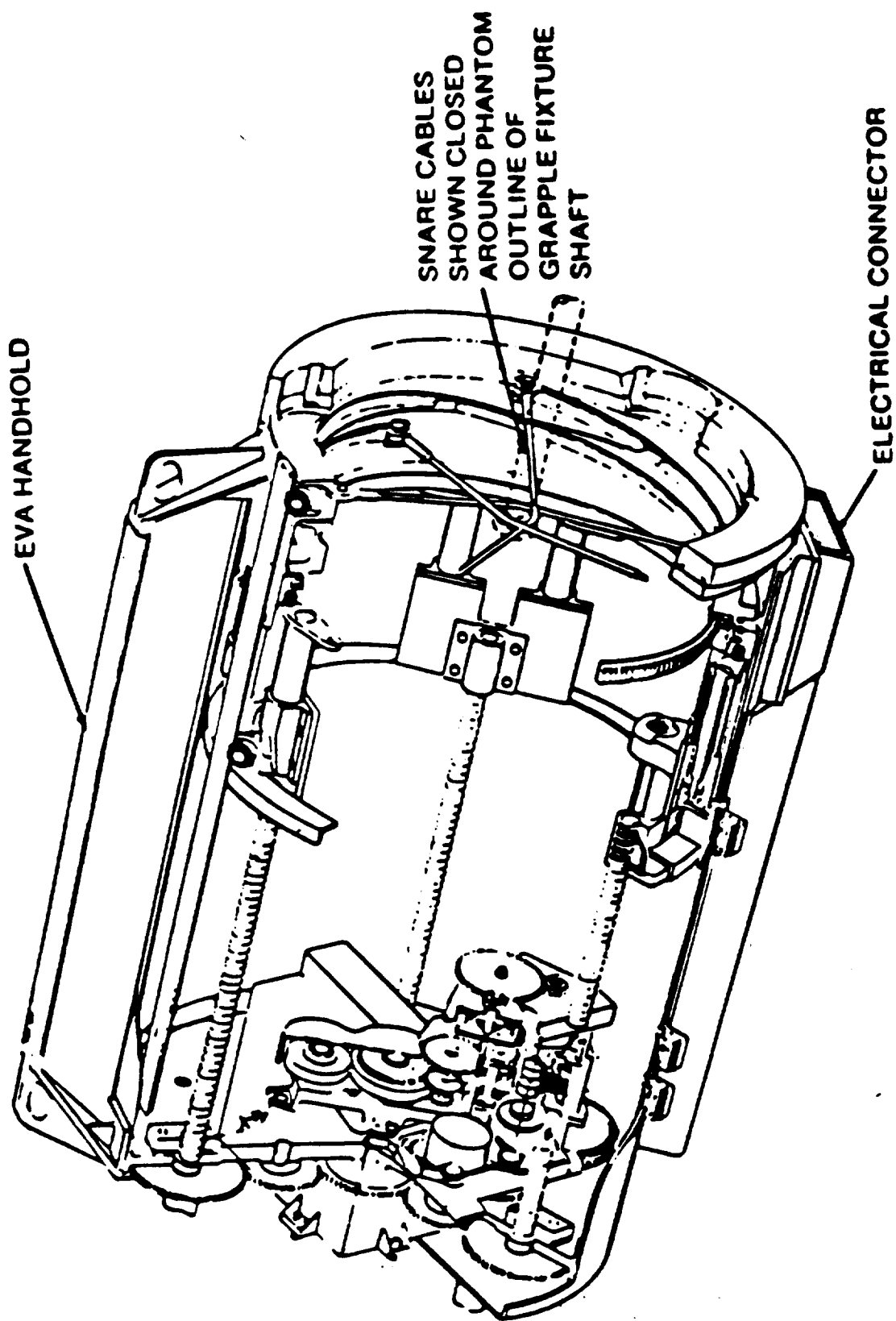
## Chapter 20. Arm End Effector Tools

End effector tools are categorized as any device that an end effector can latch onto. Many end effector tools were chosen because no single tool works best for every task. An assortment of tools will allow the arm to perform a diverse array of jobs. Small end effector tools could be built and tested on earth and then added to the Space Station as new jobs are defined. End effector tools are preferred because they are very inexpensive compared to a specialized RMS arm.

End effector tools also have the advantage of being transportable to other Space Station robotic systems, the OMV or even the Shuttle. A disadvantage of end effector tools is that they increase the number of degrees of freedom which results in a greater computing capability if real time is to be realized. Two classifications of end effector tools that this chapter addresses are arm attachments and grippers.

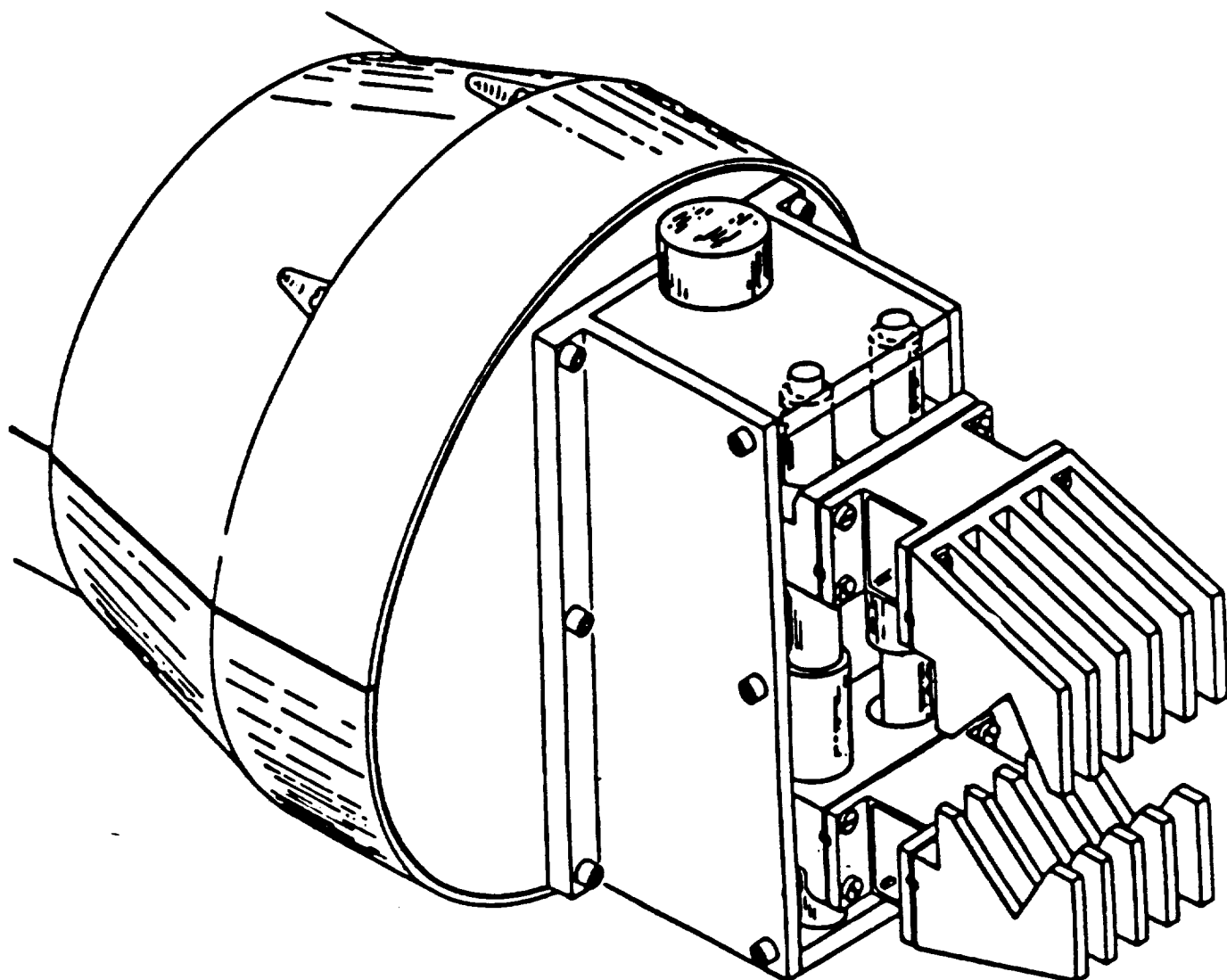
Multiple arm tools are comprised of one arm, two arm, three arm, and four arm as shown in Figures 2.11-2.14.

The one arm would serve as an independent extension of the manipulator's wrist. The number of arms could be extended out to a four arm tool which would have two main extensions from the manipulator wrist. Each main extension would have two independently operated sub-arms totaling four altogether.



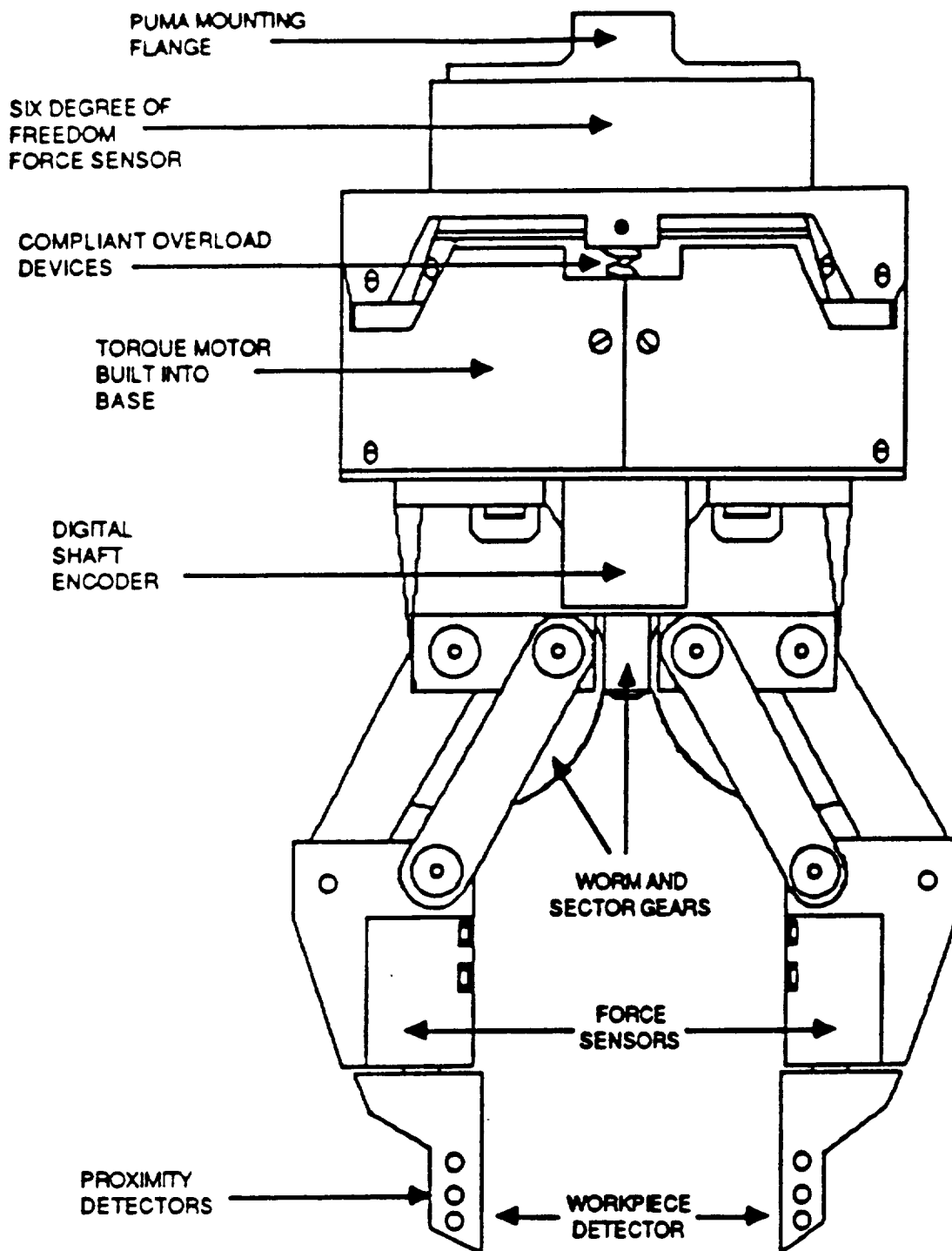
STANDARD SNARE TYPE  
END EFFECTOR

Figure 2.5



*JPL GRIPPER  
END EFFECTOR*

Figure 2.6



## *LANGLEY INTELLIGENT END EFFECTOR*

Figure 2.7

## THREE FINGER MULTIJOINTED END EFFECTOR

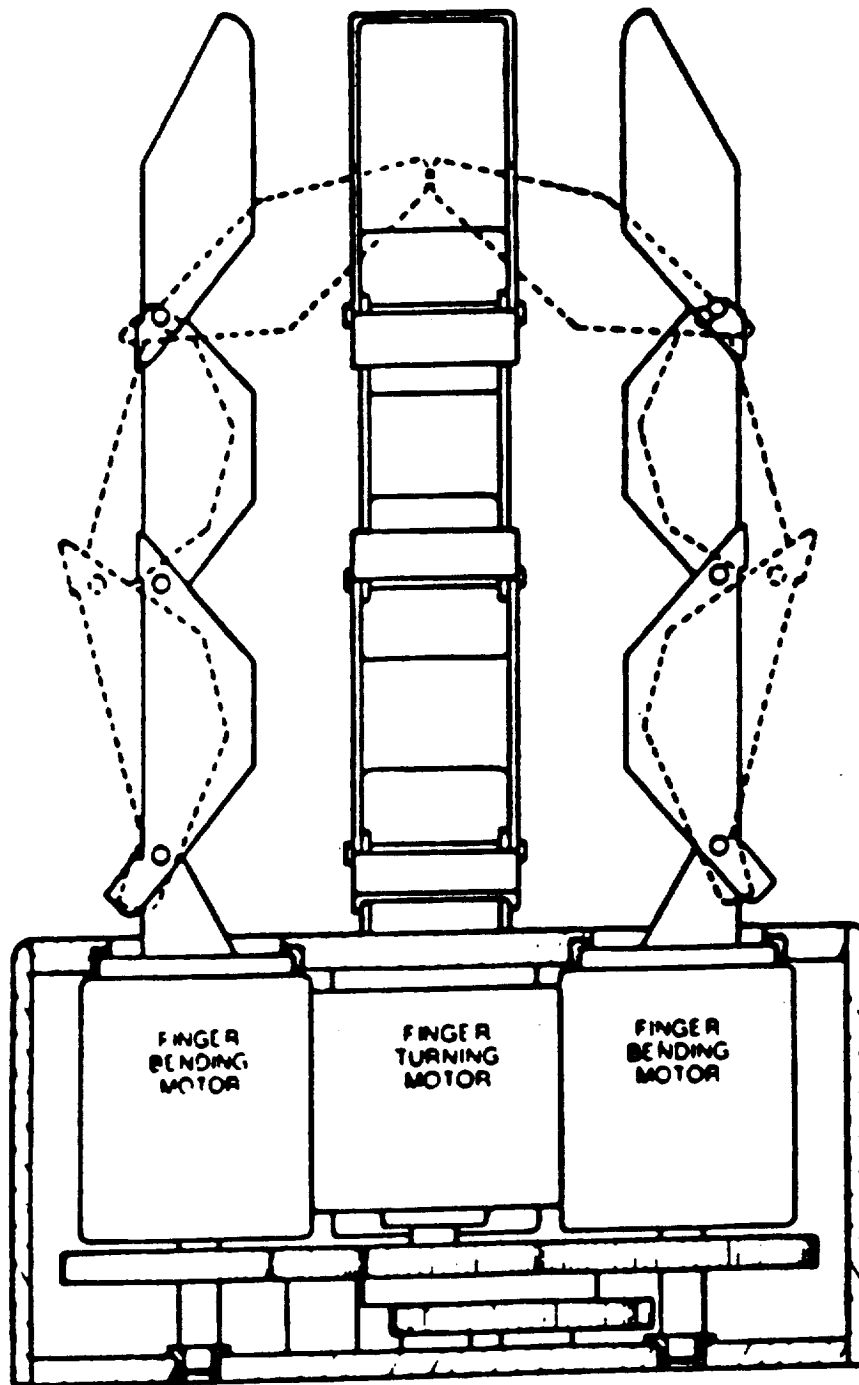
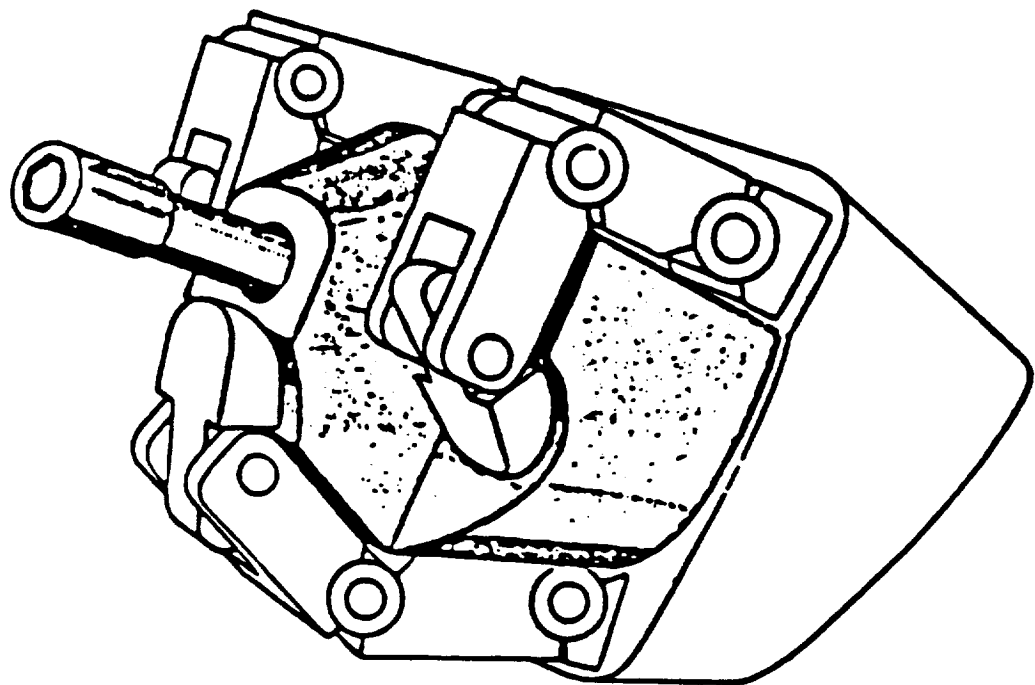
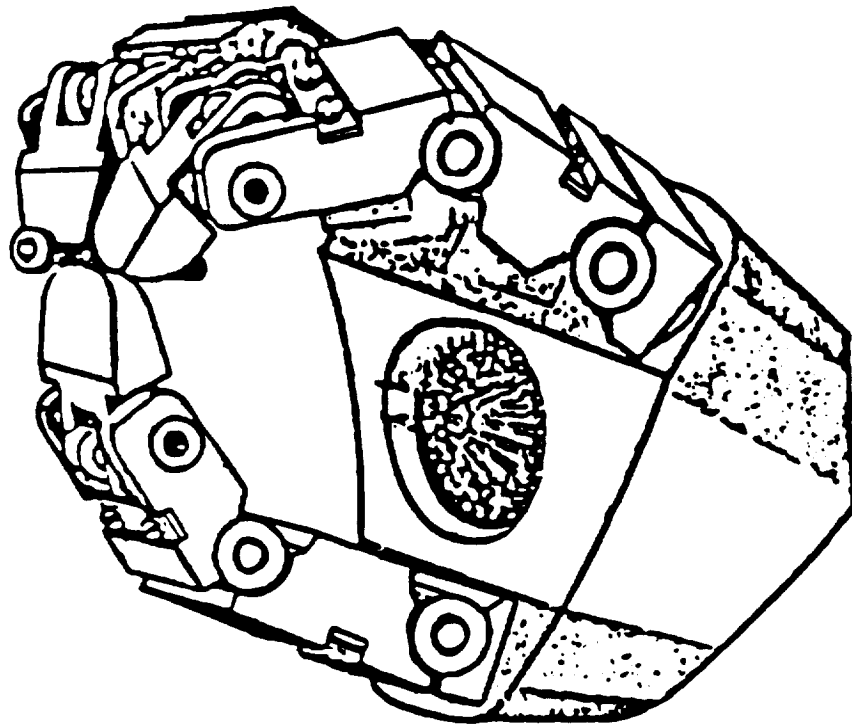


Figure 2.8





*THREE MULTIJOINTED FINGER  
END EFFECTOR*

Figure 2.9  
77

*JPL PROTOTYPE  
END EFFECTOR*

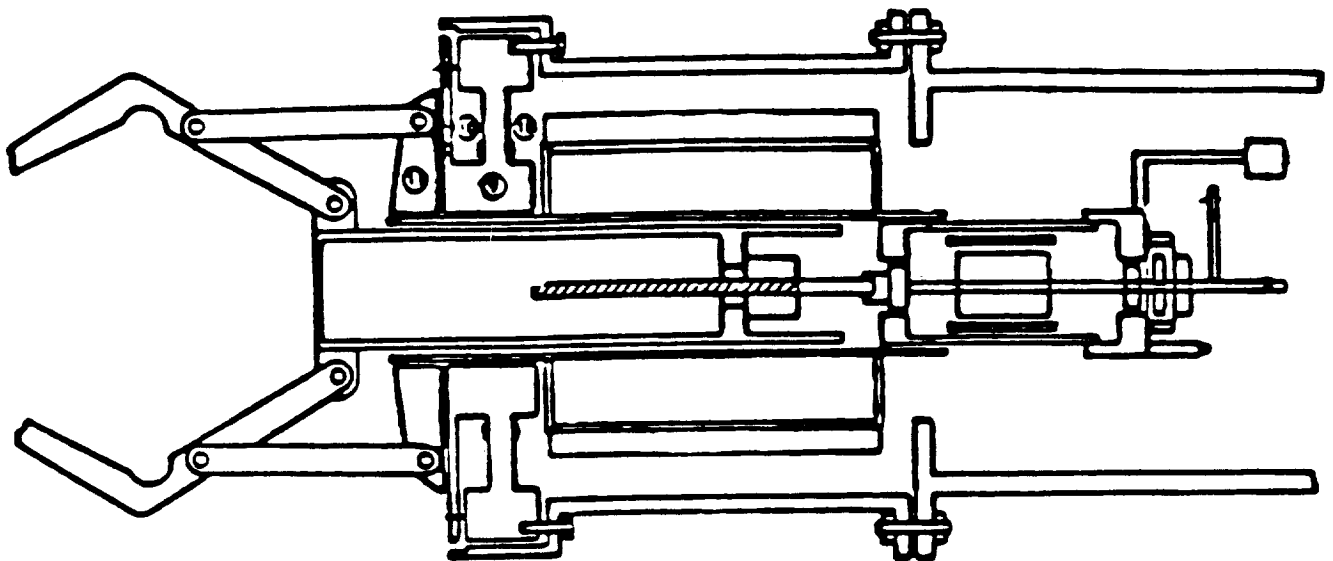


Figure 2.10

# ONE ARM END EFFECTOR TOOL

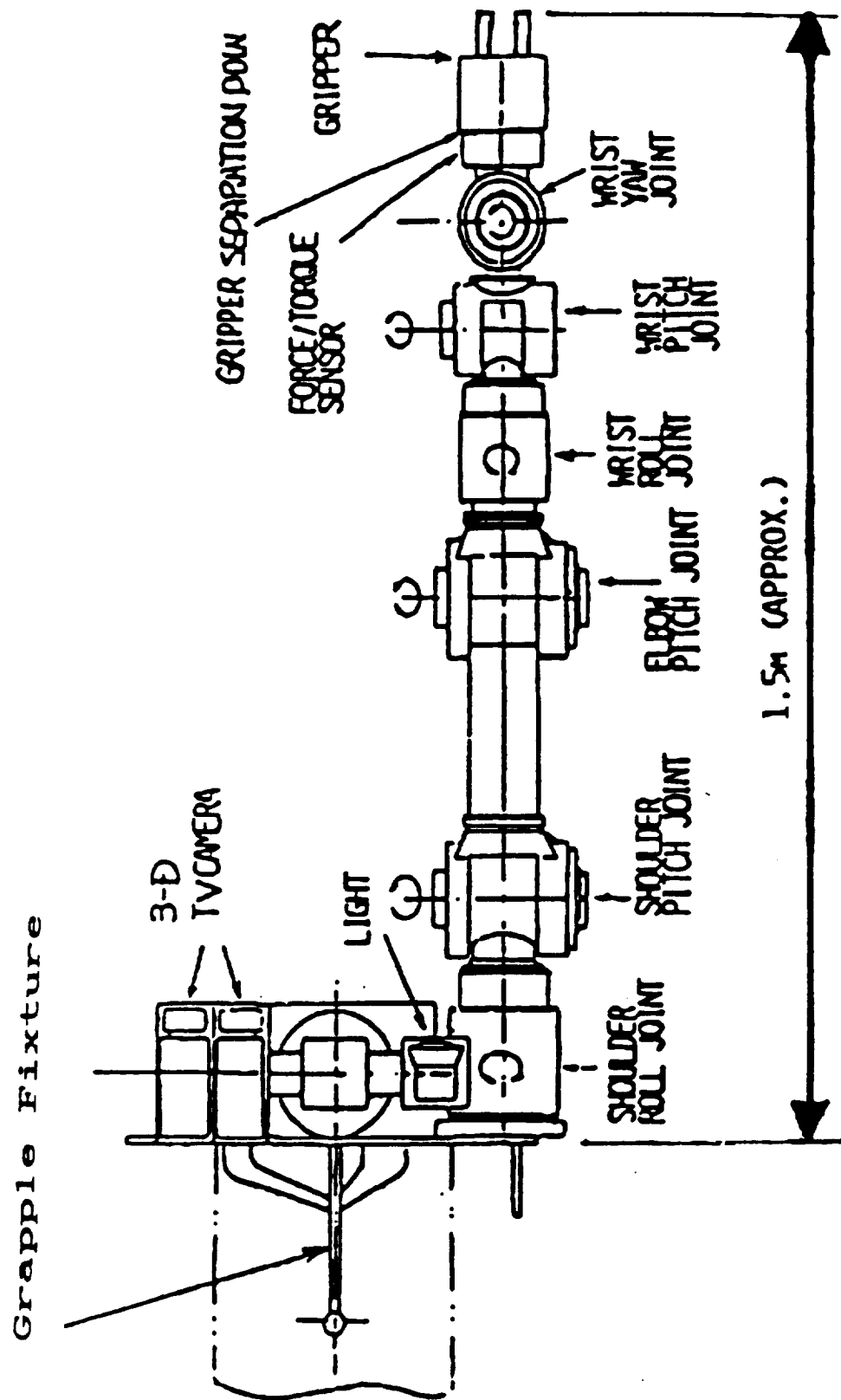


Figure 2.11

## TWO ARM END EFFECTOR TOOL

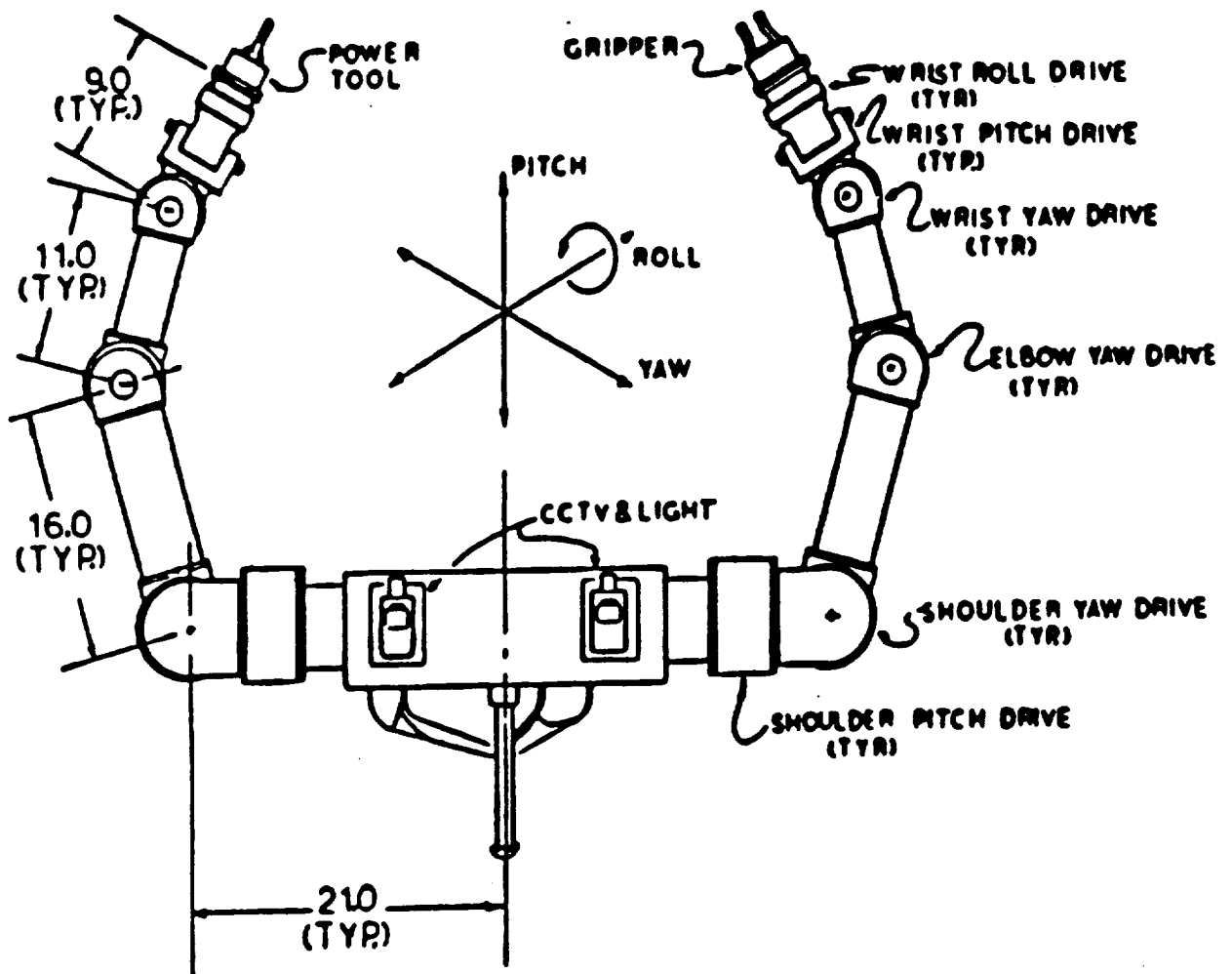


Figure 2.12

## THREE ARM END EFFECTOR TOOL

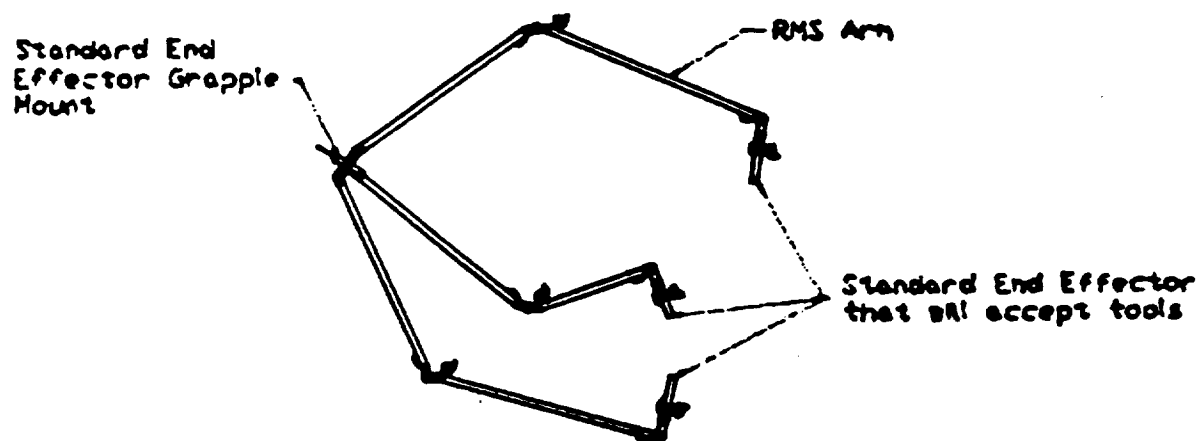


Figure 2.13

*FOUR ARM  
END EFFECTOR TOOL*

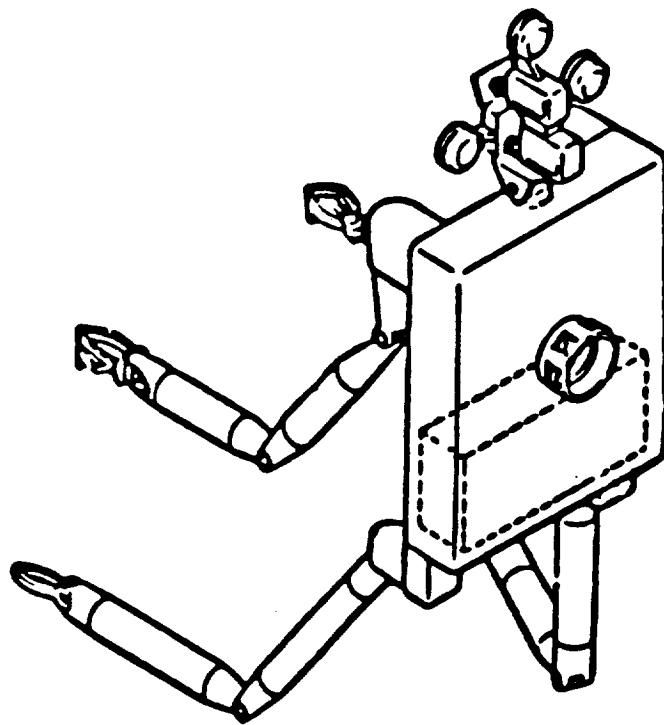


Figure 2.14

*VERSAGRIP III GRIPPER  
END EFFECTOR TOOL*

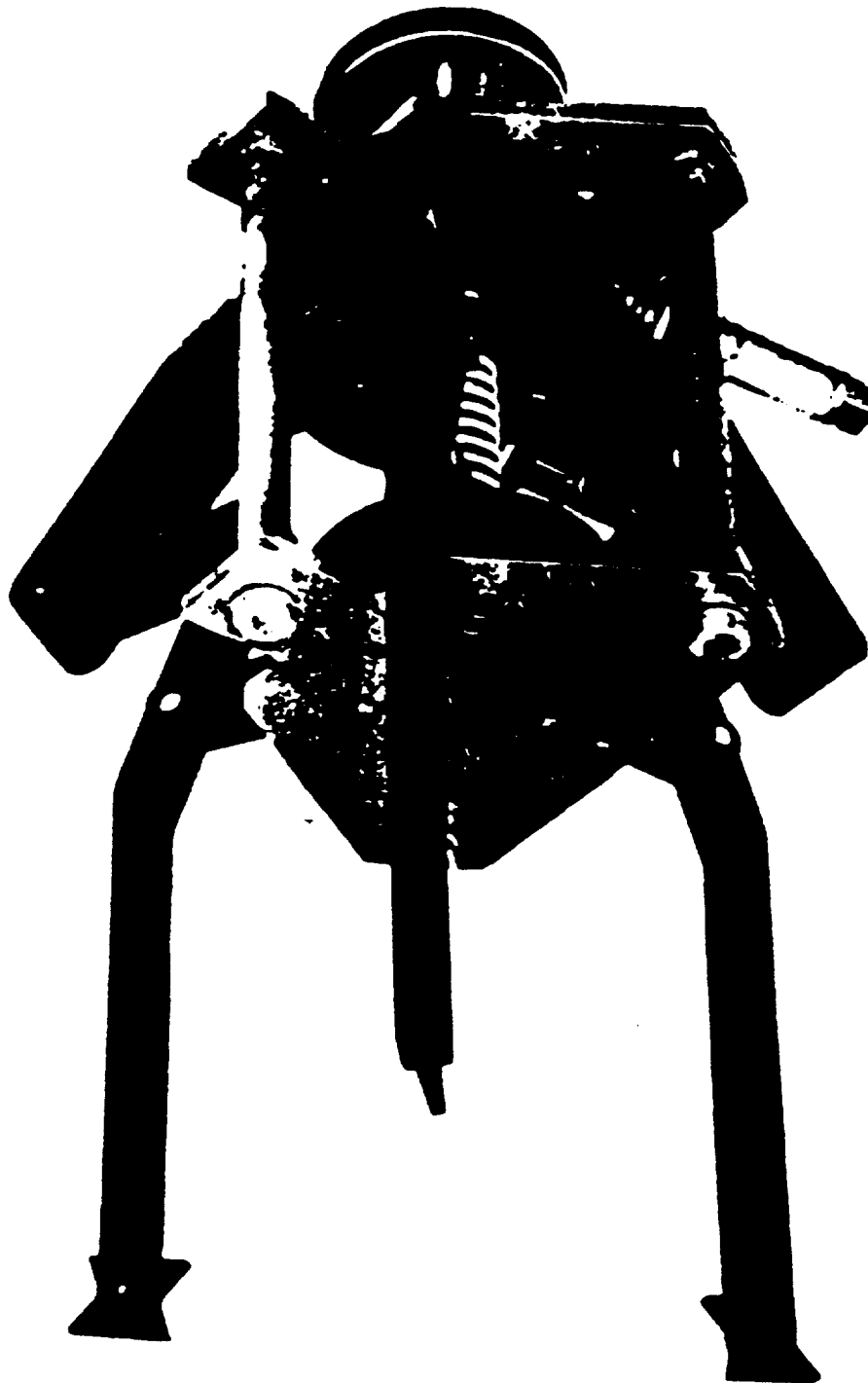
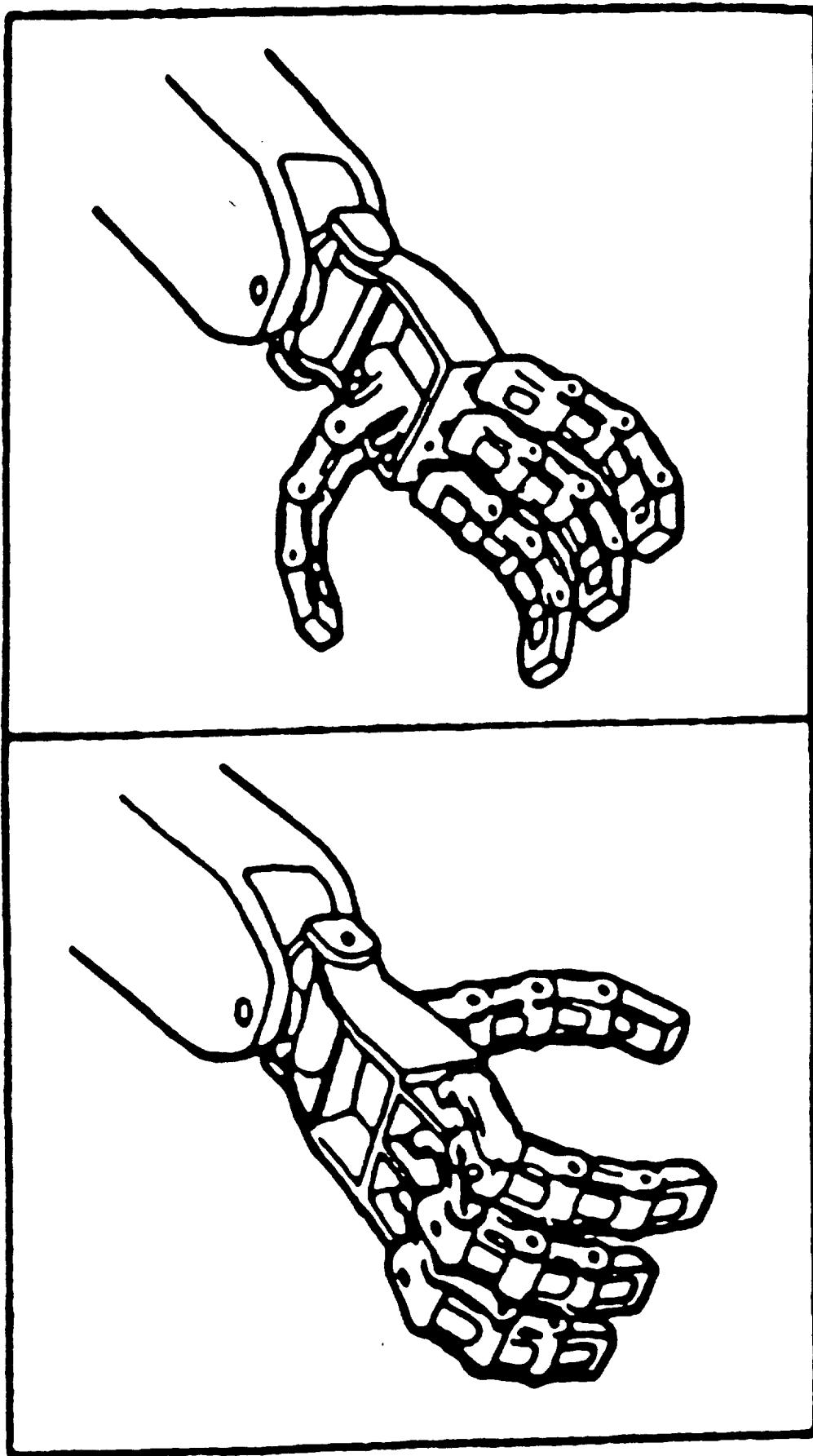


Figure 2.15

FOUR FINGER GRIPPER  
END EFFECTOR TOOL





## MAGNETIC GRAPPLE GRIPPER END EFFECTOR TOOL

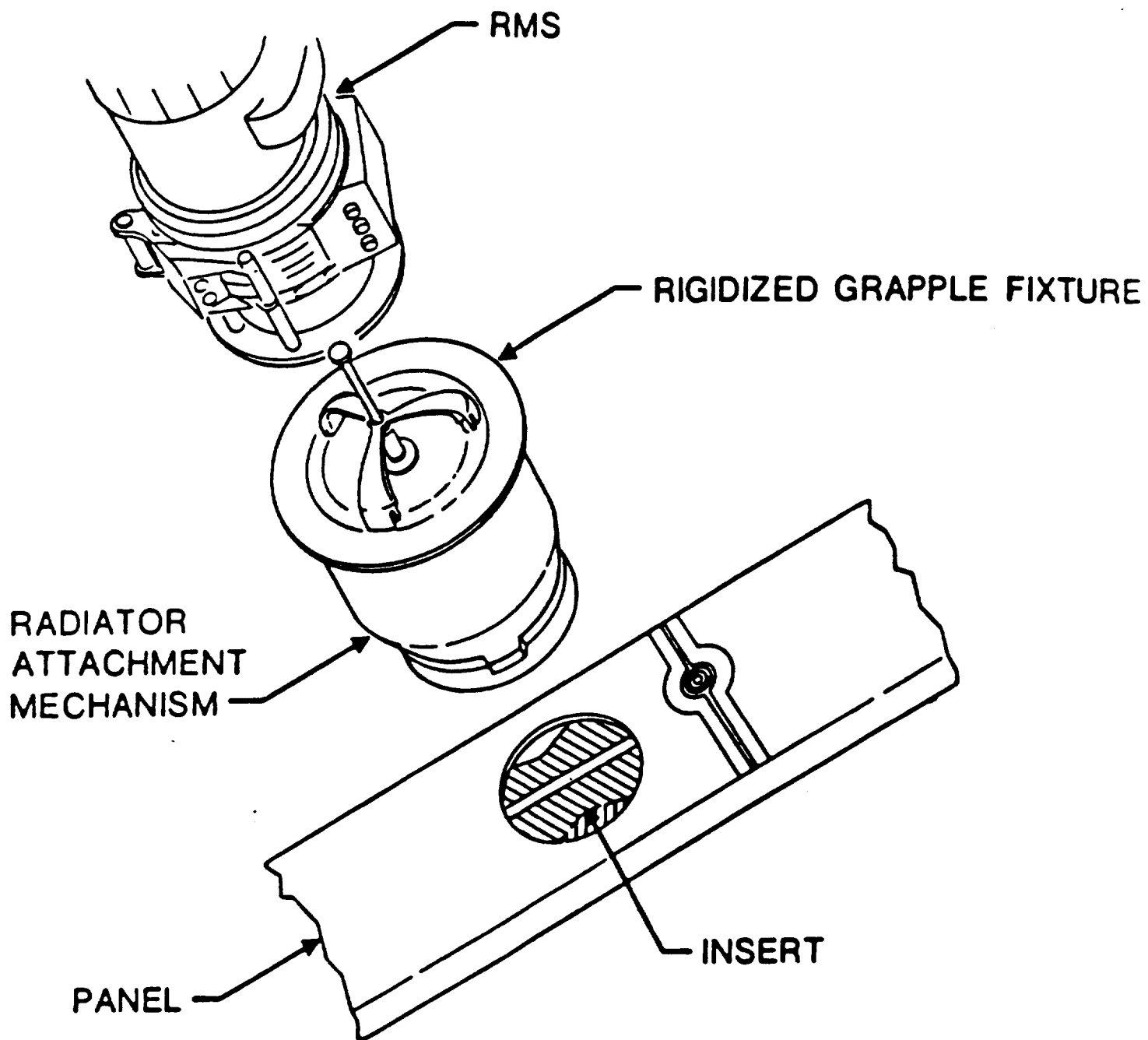
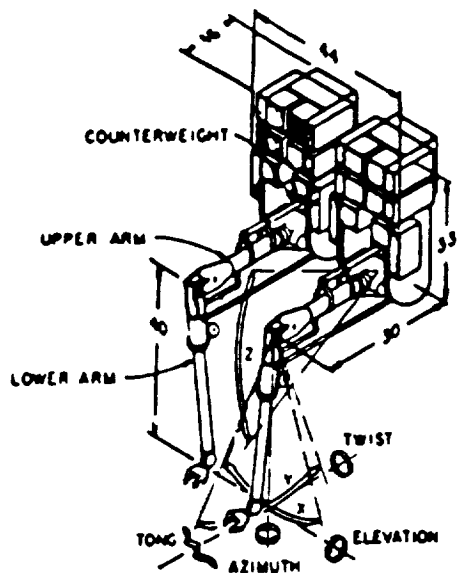
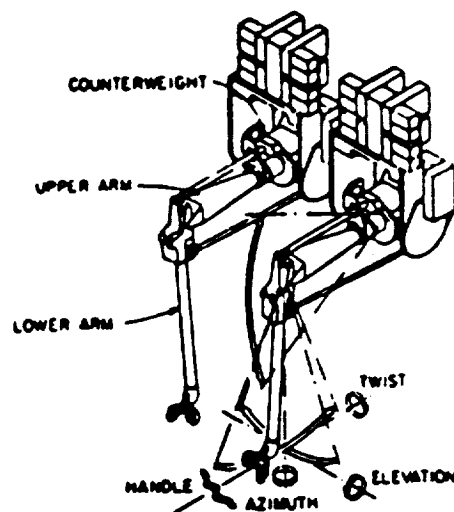


Figure 2.17

# SERVO MASTER-SLAVE CONTROL SYSTEM



ARGONNE MARK E4A SLAVE MANIPULATORS



ARGONNE MARK E4A MASTER MANIPULATORS

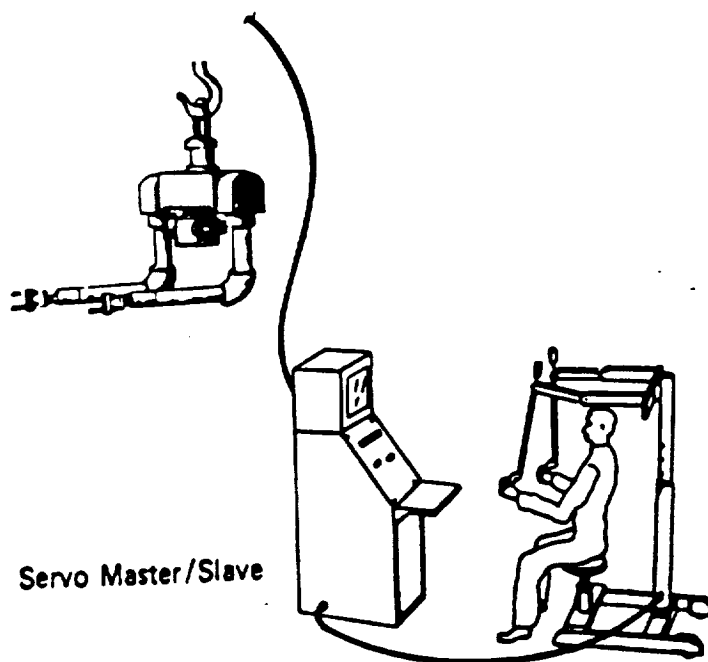
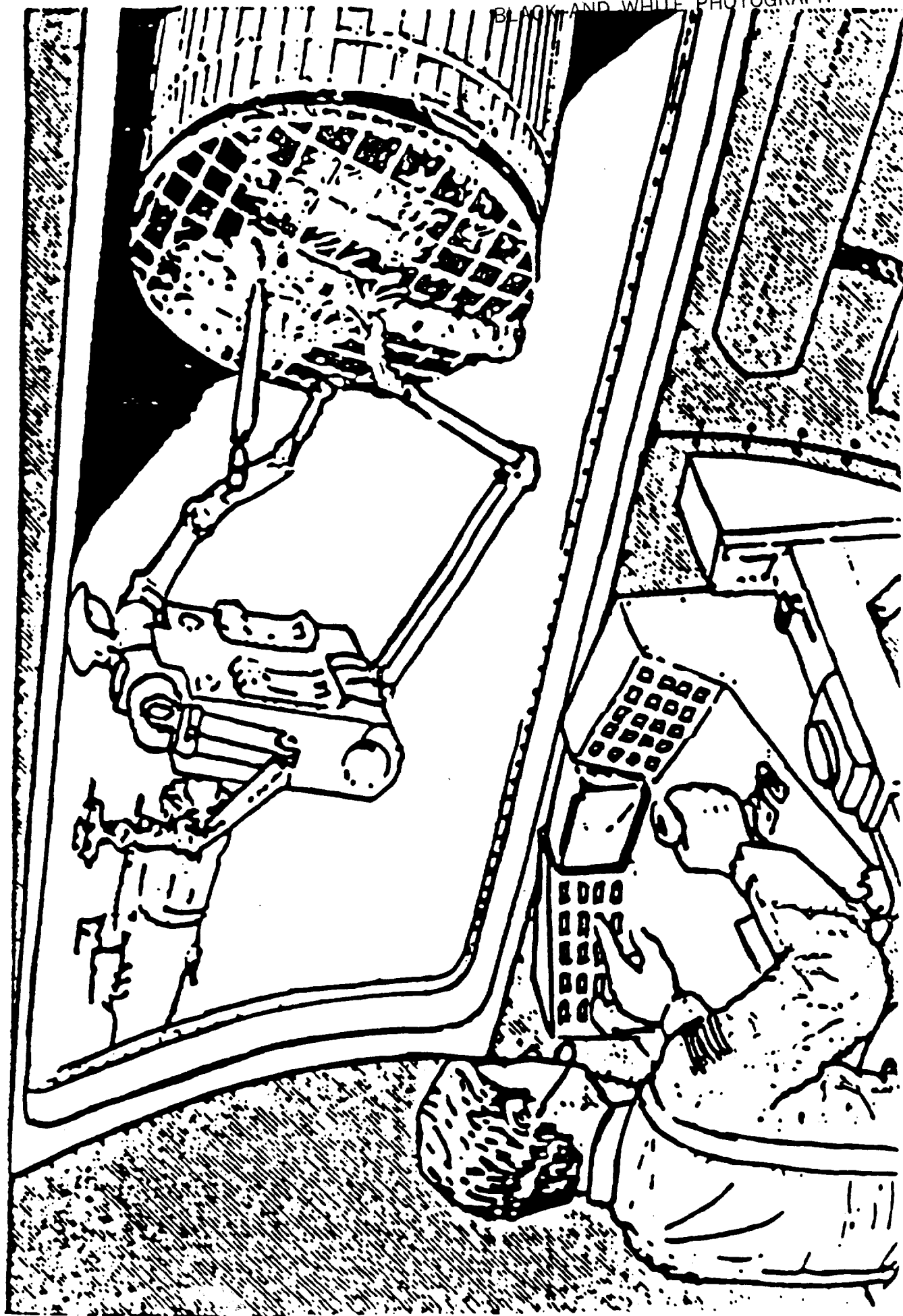


Figure 2.18



TELEROBOTIC  
CONTROL SYSTEM

Figure 2.19

# AUTONOMOUS CONTROL SYTEM

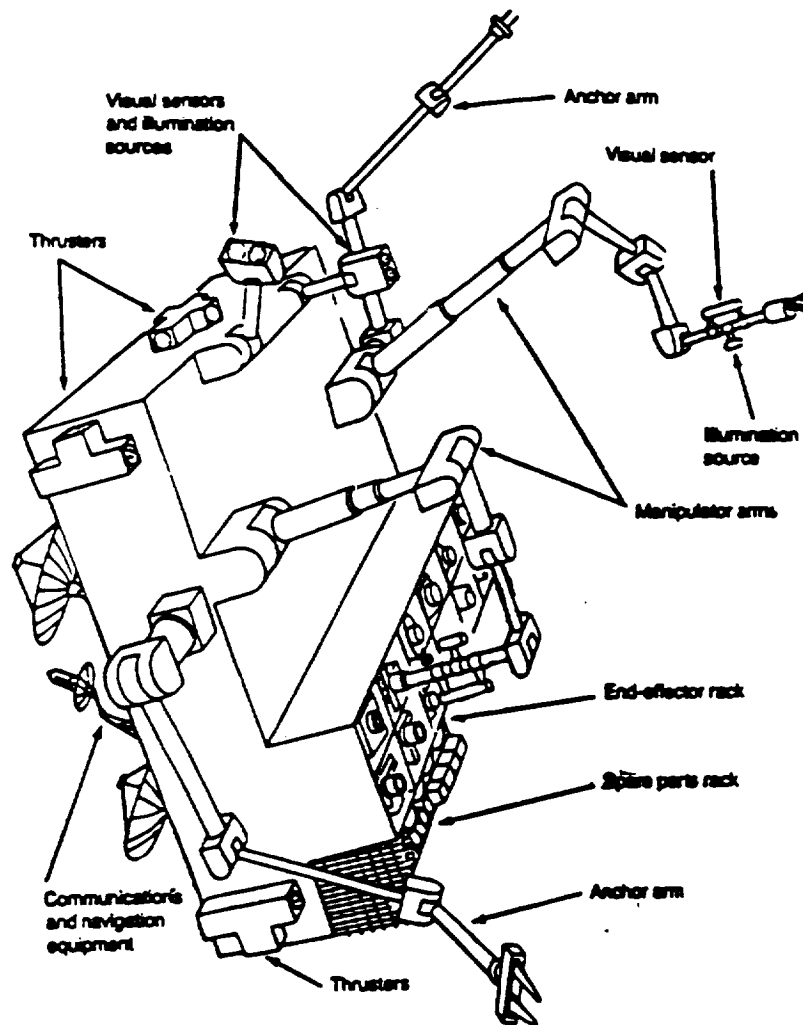


Figure 2.20

# SPACE SHUTTLE RMS CONTROL SYSTEM

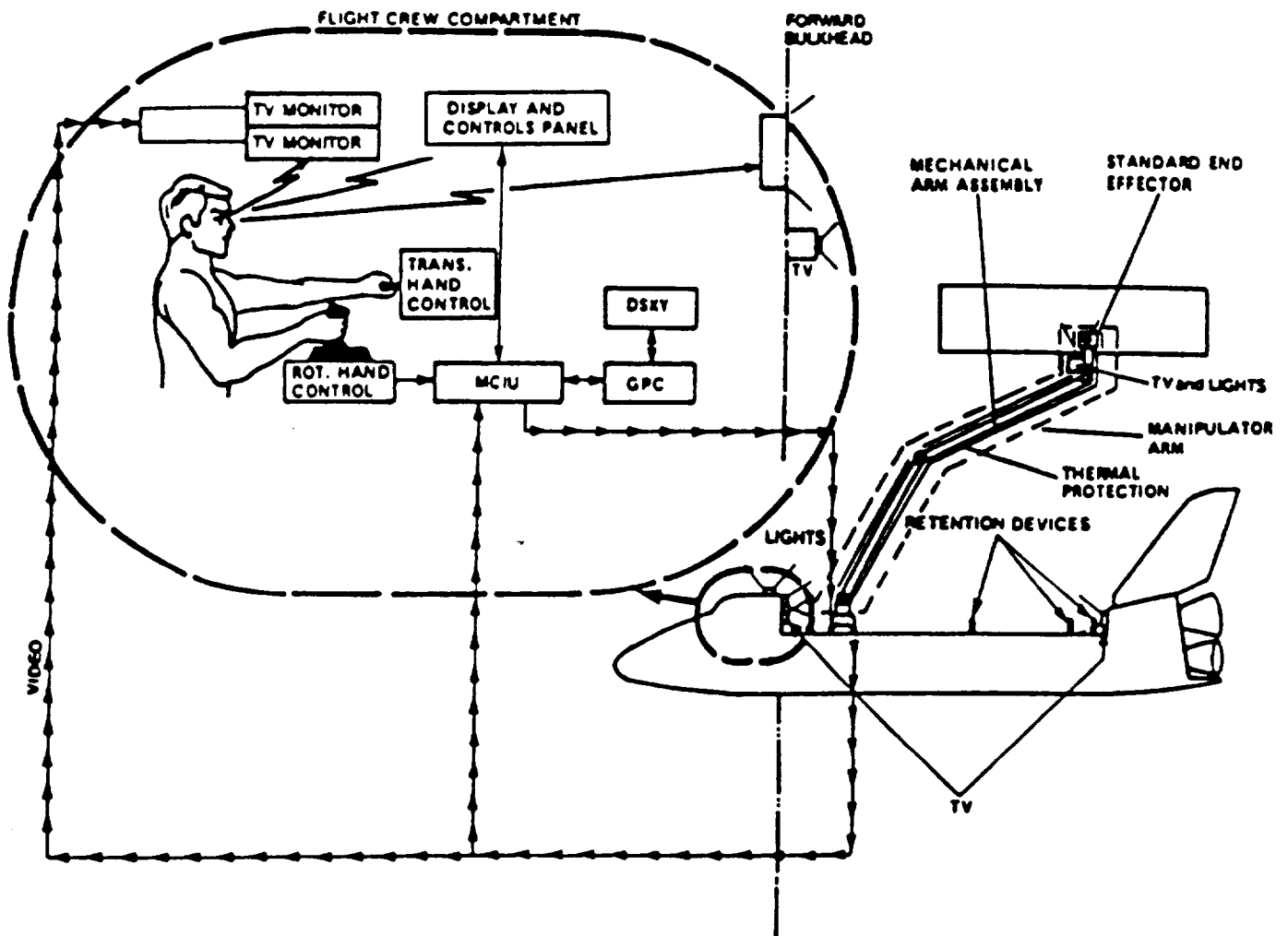


Figure 2.21

## Chapter 21. Gripper End Effector Tools

Several grippers were investigated, five of which are shown in Figures 2.6-2.10. Additional gripper tools researched are shown in Figures 2.15-2.17. Note that the end effectors in Figures 2.6-2.10 may be considered both as end effectors and end effector gripper tools. The figures include the JPL Gripper, Langley Intelligent, JPL Prototype, Versagrip III, 3 finger multijointed, 3 multijointed finger, the 4 finger Gripper, and magnetic grapple. All of these grippers are either in the design or prototype stages.

## Chapter 22. Control Systems

Three types of control systems will be addressed in this chapter. They include teleoperations, telerobotics, and autonomous control.

Teleoperations is the simplest and oldest of the three. Teleoperations is a system where the arm would be totally controlled by the operator without any computer assistance. An example of teleoperations would be a master slave arm assembly as shown in Figure 2.18.

Telerobotics deals with a system that is partially computer aided and/or controlled as shown in Figure 2.19. With partial computer aid, the computer would suggest a method of operation and let the operator decide if it was reasonable. With partial computer control, simple operations such as grappling will be done automatically.

Autonomous control is the most advanced control method. It will allow for practically no human supervision. Figure 2.20 shows an autonomous orbital repair vehicle. Complete autonomous control is still in the early development stage.

## Chapter 23. Man-Machine Interface

The man-machine interfaces are discussed in this chapter. Four types have been considered. The first interface addressed is joystick control.

Joystick control is used to control the SRMS. A rendition of the SRMS joystick system is shown in Figure 2.21. When two joysticks are used, one can control the three translational movements of the manipulator, while the second joystick will control the three rotational movements. If velocity or force reflection is incorporated into the control, then velocity or force can be sensed by the operator by the force imposed on the joystick. Proper scaling of forces is required to avoid operator fatigue. Joystick

control is particularly good when the working area of the operator is limited, but it does not emulate the dexterity of the human hand very well.

Master-Slave arm, as shown in Figure 2.18, controls the movements of the manipulator by duplicating the movements imposed on the master arm. The master controller is kinematically identical to the manipulator. This allows for a high degree of proprioceptive feedback. This is a good method when control of the arm is very important. The ability to sense the force being applied to the manipulator is usually provided to the operator via force reflection. When this controller is used with servocontrol, a high degree of accuracy and controllability is achieved with less operator training. This is beneficial when the arm is not in constant use.

A major disadvantage to this controller for TERMS is that the scaling factors are typically small, ranging from 3:1. For the 48 foot SRMS, a 16 foot long master would result.[13]

Exoskeletal control, on the other hand, duplicates the intricate motions of the manipulator easily, and does so in much smaller space than master-slave control. The operator's arm or hand fits inside a sleeve or a glove. The movement imposed on the glove or sleeve are duplicated by the manipulator. Exoskeletal control allows the operator to communicate movements to the manipulator in a manner most natural to him.

A fourth method of control is helmet mounted aiming controlled vision. This method directs the manipulator to move in the direction the operator's head is pointed towards. This method is good for large, rather than fine, movements. The manipulator on the elevator will need to make both large and fine movements. It may be best to incorporate more than one means of control.

## Chapter 24. Drive Methods

This chapter addresses the drive method of the manipulator. Two basic types surfaced that are good for space applications. Both are servocontrolled. Servocontrol uses individual joint commands to direct the manipulator which automatically locks into any position commanded. The actual and desired positions of the manipulator are compared. If the difference is large, a signal is sent to the actuator to adjust position.

Electromechanical driven servomanipulators are widely used in both space and industrial applications. The SRMS has

electromechanically driven joints. This type of control should not be used where sparks are a hazard.

The second type of drive method is a digitally driven servomanipulator. Large cable bundles are reduced to coaxial cables for control and television signals. It is inherently flexible by virtue of its software implementation and is less susceptible to drift due to thermal instability problems. It is more reliable than analog and position accuracy is improved.[13]

## Chapter 25. Manipulator System Optimal Solution - Phase I

The fixed mount design was chosen as the optimal solution among the mechanical connections for the elevator interface. Solution Matrix 2.1 contains both the mechanical and electrical elevator interfaces.

The primary reasons for the selection of the fixed mount were: safety, initial cost, EVA, human interface and simplicity. Among the three designs, a fixed mount was deemed safer because it is rigidly attached to the elevator instead of being mobile or transportable. A track drive has the possibility of catching an astronaut during an EVA. The fixed mount is slightly safer than the quick mount because it will not have the ability to free float in the event of an accidental uncontrolled removal.

The initial cost of the fixed mount is lower than the other two interfaces. It is very inexpensive to bolt, glue or weld compared to designing and manufacturing a quick change mechanism or track drive system.

The fixed mount and quick mount designs are on an equal level when it comes to an EVA, however a track drive interface takes considerably more time to properly align and position on the elevator. During an EVA the human interface time is very minimal for a fixed mount. Both quick mount and track drive may require an EVA for attachment and detachment.

As a final consideration a fixed mount is superior when it comes to simplicity. The fixed mount is a connection comprised of a plate attached to the elevator by either bolts, glue, or welds. The quick release is more complicated because of the parts that must interface and move together. The track drive is orders of magnitude more complex because of the motors, moving parts, power, etc.

The multipin connection design was chosen as the best type of electrical connection for the arm-elevator interface. The design considerations which allowed the multipin connector to surpass the coaxial cone connector were safety, initial cost and reliability.



During an EVA the coaxial cone connector was deemed unsafe because of the exposed power channel. The multipin connection has all of the power and data channels shielded from accidental contact. The initial cost of obtaining a multipin connection was much less than for a coaxial cone connection.

Multipin connections are the most predominant types of connections for multichannel power and data lines and are commercially available everywhere. Coaxial cone connections are not a common type of connection for both power and mass data communications. Multipin connections are more reliable than coaxial cone connections when it comes to contact force and vibration. A coaxial cone connection needs a constantly applied contact force in order to maintain surface contact. If the contact force is lost, the connection will be broken. A multipin connection does not need a constantly applied force to maintain contact. It should be pointed out that the installation of a snap on the connection was ruled out because of the need to disconnect without an EVA.

A multipin connection has better wear characteristics than a coaxial cone connection when it is under a vibrational load. The multipin connection has more contact surface which allows for more holding power and the pins also help to make for a rigid connection. During vibration the coaxial cone connector will have a tendency to rotate and pull out. If the vibrational displacement becomes excessive the connection will become damaged due to electrical arcing.

The SEE won among the six end effectors. For a detailed evaluation of the end effectors see the End Effectors Solution Matrix 2.2. The primary reasons that the SEE won were safety, initial cost, technical availability and tool interface.

With respect to safety the SEE won over the other five because it had the least potential for grabbing an astronaut during an EVA and trapping or crushing a body part of an astronaut. The SEE is initially cheaper than any of the other designs because it has already been made, tested and proven in space. The other models are still in the prototype stages and have not been proven in space.

When it comes to technical availability the SEE not only has been built, tested and proven in space, but it also has the accompanying software to interface with the human operators. The other models can easily be built; but, the software has not been development.

Lastly, the SEE was more desirable than the other models for tool interfacing. The SEE can rigidize any tool that has a standard grapple fixture and also can supply power and data

relay connections. Presently none of the other end effectors have a power and data communications connection. None of the other end effectors have the ability to hold a tool at more than one point location. The SEE can hold a tool in two point locations (ie. hold in two parallel planes separated by a distance).

The two arm end effector tool barely won out over the one arm tool, and heartily beat out the three and four arm tools. For more details on the solution optimization of the arm tools see Solution Matrix 2.3. The only major reasons why the two arm tool won over the one arm tool was operational performance. It was felt that a human operator could more naturally control two arms which would mimic himself.

The three and four arm tools lost 85% of the time to the one or two arm tools. The four arm tool had very high ratings in operational performance, dexterity and flexibility, but it was the lowest in almost every other design consideration which made the design unattractive.

Both the JPL gripper and the Langley Intelligent end effector were chosen as the gripper end effector tools over the remaining seven. For a more detailed breakdown on the solution optimization process see Solution Matrix 2.4. The two grippers came very close in almost all design considerations. The magnetic grapple lost solely because it was not dexterous, even though it led in most every other category.

The jointed finger designs did not win because their scores were low in every category except operational performance, dexterity and flexibility.

For the control system telerobotics beat teleoperations and autonomous. For a detailed design solution optimization process see Matrix 2.5. An interesting point about the solution optimization matrix is that the overall winner won only one design consideration.

Telerobotics did well in almost every design consideration, however the two other fluctuated wildly on design considerations. The reasons why telerobotics won were that it had the simplicity and availability of teleoperations and the computer aided features that autonomous control could provide.

Both joystick and exoskeletal control were selected to interface between the operator and the manipulator. A pair of joysticks will serve as the primary control of the manipulator while the exoskeletal will supplement the joysticks by controlling the more dexterous movements of the

end effector and its tools. The joystick was superior to the master-slave in the areas of mass and size. The master-slave would require an unacceptable amount of room on the Space Station.

Areas where the joystick control lacked were in dexterity, flexibility, and human interface. Those areas are compensated for when the exoskeletal control is also used.

The reason exoskeletal is not used solely is because it makes fine intricate motions but does not perform sweeping movements well.

The digitally driven servomanipulator was chosen over electromechanically driven. (Matrix 2.7) This was due largely to the greater degree of dexterity and flexibility afforded by digitally driven servomanipulators. It also was judged to have a much higher operational performance because it is less susceptible to drift.

## DESIGN PHASE II. TETHERED ELEVATOR REMOTE MANIPULATOR SYSTEM

### Chapter 26. COMPUTER HARDWARE SYSTEM

The computer which makes up the central processing unit (CPU) must successfully integrate software and feedback data links, support complex calculations in a short time, and maintain control of the entire system. Three types of CPU's, which have potential for use on TERMS, were looked at. These included:

1. Digital Equipment Corp. DEC VAX II CPU
2. Motorola 68000 series CPU
3. IBM AP-101 CPU

#### 26.1 DEC VAX II CPU

The Digital Equipment Corporation's DEC VAX II has some qualities which make it worthy of consideration. A few of these qualities include:

- \* The DEC VAX II provides data management facilities at two independent levels where one level can override the other if discrepancies occur.[17]
- \* Internal architecture features a condition handling facility which can supply a warning or possibly correct for unseen changes in operating conditions.
- \* DEC VAX II fulfills the need for coupled multiprocessing systems.[17] If more than one CPU is required, this feature is a necessity.

One aspect of this system which makes its use undesirable for use on TERMS and the tethered elevator as a whole, is its inability to meet size constraints.

#### 26.2 Motorola 68000 Series CPU

The Motorola 68000 series CPU is being considered for the following favorable aspects:

- \* The 68000 series CPU supports high level languages necessary for fast response time.
- \* The 68000 provides flexibility if a need for a coupled multiprocessing system arises.

- \* The 68000 provides an advanced architecture to handle simple as well as complex calculations efficiently.[18]

As with DEC VAX II system, the Motorola 68000 series CPU may not provide for the compactness necessary for use on TERMS.

### 26.3 IBM AP-101

The IBM AP-101 CPU is being considered, at this time, as the most favorable system for use on TERMS. The AP-101 has already proven its worthiness in space. Five AP-101's are currently employed on each space shuttle.[19] Some other qualities include the following:

- \* An input-output processor (IOP) to control and monitor data bus traffic relieving the CPU of these time consuming tasks.
- \* The capability of handling over 400,000 full over 400,000 full word operations per second.
- \* Provisions for a ninety-five percent detection rate of hardware failure which could affect computer operation.

The IBM AP-101 also provides clock synchronization, central control, and handling of interrupts.[20] What makes this CPU much more feasible than the others, besides its track record in space, is its size. The dimensions of the IBM AP-101 are twenty inches by nine inches by six inches.[20]

## Chapter 27. DATA TRANSFER DEVICES

The control of the remote manipulator arm will require high-speed transmission of large amounts of data from the Space Station's computer systems to those of the tethered elevator. The digital communication link, part of the general Space Station support facilities, should be capable of transmitting all necessary sensory and control information between an operator and the remote manipulator arm. Possible means for supplying this might involve:

1. Packet Radio Techniques.
2. Wide-Bandwidth Modulation of Laser Beams.

### 3. Fiber Optics Cable System.

### 4. Electrical Transmission Routing by Wideband Cable.

The requirements of the data transmission link are dictated by the application of sensing devices, automated camera control of the manipulator arm, and command distribution to the remote station. In addition, the handling of the data of many experiments for science and application missions conducted along the tether could produce a data stream of up to three hundred megabits per second.[21] Thus, techniques for data transmission which can effectively handle a load of several megabits per second of information shall be discussed.

#### 27.1 Packet Radio

Packet radio techniques represent an evolution of wireless message-switching techniques. Data information is assembled in short messages (packets) that are transmitted by users. Antennas for transmitting and receiving electromagnetic waves should be mounted on the tethered elevator and the Space Station. At microwave frequencies, relatively small size structures are capable of directing energy into narrow beams of a few degrees of divergence.[22] This is important for TERMS since the signals must be directed to an intended coverage area. In light of the requirements of TERMS, a scanning spot-beam concept is applicable. This concept combines the wide area accessibility of an area coverage system with the high antenna gain of a spot-beam system. The important features of this concept are:

- \* Full-band digital transmission of beams operating at 30/20 GHz.
- \* Rapid, synchronized scanning of the up-link and down-link beams.
- \* Automatic beam forming of the up-link and down-link beams.
- \* High-speed operation.
- \* Computer control of all of the above.

The concept appears to be capable of a data transmission rate of six hundred megabits per second.[22] Thus the rate requirements of TERMS can be satisfied using this method. Implementation of the scanning beam concept requires several technological innovations. Since the elevator may be located at any position along the tether, a method whereby the beam could be made to scan is necessary.

The original scanning beam concept was based upon a phased array antenna. This is an array of many small radiating elements, each of which is preceded by a device that can shift the phase of the microwave signal passed through it. By assigning a particular phase to each element's emitted wave, superposition can be used to exhibit a planar wavefront, creating a beam focused in a particular direction. This direction can be altered by changing the settings of individual elements. This eliminates the need for a mechanism to alter the orientation of the entire antenna.

An alternative to the array is an antenna consisting of a large reflector that could be illuminated from varying directions. The resulting beam can be made to focus in one of many possible directions.[23] Thus, the scanning spot-beam concept for the packet radio technique appears to be a feasible means for effective data transfer to and from the Space Station and the remote manipulator arm.

## 27.2 Laser Beam

A second possible means of digital data transmission is laser communications. The interest in laser communications for TERMS' applications stems from the much higher operating frequencies, several orders of magnitude higher than radio frequency systems. This provides three main advantages.[24] These are:

- \* Greater bandwidth.
- \* Smaller beam divergence angles.
- \* Smaller antennas.

There are a multitude of laser types usable as sources for laser communications systems. Laser types are normally identified by the type of material that is used as the "gain medium". The three types most often considered for use in communications systems are:

1. Gas lasers.
2. Solid-state lasers.
3. Semiconductor lasers.

Selection of which laser is to be used for a particular communications systems is dependent upon a number of factors including data link range, propagation medium, required data rate, and platform mounting limitations.[24] Obviously strict adherence to the limitations of these factors is required for the optimization of the data link. Both radio frequency and laser data communications systems utilize the propagation of electromagnetic energy to transmit information across the link. There are two options for space proven

laser sources:

1. The semiconductor laser diode.
2. The solid-state diode-pumped Neodymium: yttrium, aluminum, garnet laser (Nd:YAG).

Systems using the laser diode generally employ direct modulation of the diode drive current and are somewhat limited as to the data rate and range as compared to the diode-pumped Nd:YAG laser systems. However, for some applications, the advantages in efficiency and weight for laser diodes may outweigh its limitations.[24] This is of prime consideration for the design of TERMS.

### 27.3 Fiber Optic Cable

A third alternative for data communications is a fiber optics cable system. If a very fine fiber of glass or plastic receives light at one end, it will be transmitted, with some line attenuation, to the other end by means of internal reflection at the surface.[25] When an incoherent bundle is used, it will transmit a single signal of light with wavelengths in the range of 0.4 to 0.8 micrometers and frequencies between  $0.13\text{E-}15$  and  $0.26\text{E-}15$  Hertz. This light signal can be used over distances of several kilometers to transmit digital signals of very great informational content because of the very high frequency.[26] This data link appears to be appropriate since the proposed length of the tether is ten kilometers.

The fiber medium is well suited to carry information flows, in either digital or analog form. Hence, the provision of one or two fibers for the control of TERMS allows a tremendous multiservice capability with data transmission possible in both directions (full duplex).[22] The provision of broadband services requiring digital capacities up to several hundreds of megabits appears feasible. Wideband transmission routes are required to transmit vision signals from the remote work site to the operator. In addition, the necessary rates of data transmission can be achieved with series modems which operate synchronously; however, the required timing must either be produced in the modem or must be supplied by the terminal data equipment.

In regard to any possible mutual interference (noise) between the fiber optics lines, there are no problems with fiber optics solely used for data transmission. However, if other communications systems are in operation along the fiber, interference with data transmission would occur.[27] Thus, it is necessary to maintain a coordinated communications network on the Space Station.



## 27.4 Coaxial Cable

In addition to fiber optics, there are a multitude of cables available to allow rapid transmission of large rates of digital data. Coaxial lines would be applicable to the high frequency requirements of TERMS. A high operating frequency is required since line attenuation decreases as frequency rises.

A telegraphic transmission system consists basically of a transmitter, a transmission route (channel), and a receiver. By means of the digital process, the message to the remote manipulator arm is converted into a series of electrical binary signals. These signals are then transmitted to the receiver via the transmission route. The electrical binary signals are then decoded by the receiver.[27] In other words, the binary states (1 or 0) are analyzed and converted into the original message.

## Chapter 28. Control System Sensors

The major data communication will consist of feedback data from the sensing devices located on the remote manipulator arm. The sensing instruments of TERMS are an integral component of the system. Because of the obvious limitations in space, man must rely on accurate, dependable, and versatile measuring instruments to provide information on the station's condition. A number of sensors are necessary to fulfill this requirement. This chapter will concentrate on the following:

1. Force / Torque Sensors
2. Position Sensors
3. Proximity Sensors
4. Tactile Sensors

### 28.1 Force / Torque

Due to the many operations that TERMS will perform where specific force and torque conditions are inherent, sensors must be placed at strategic locations to measure these quantities.

There exist many designs of force and torque sensors; however, most benefit from transducer technology. A transducer converts a mechanical input into an electrical output. There are three main types of force and torque transducers which can be suggested for feasible means to the control of TERMS. Resistive and piezoresistive, or semiconductor, are the two significant transducer types. The non-resistive, the third type, does not find many

applications within a robotic structure; however, it can be used in some of the peripheral systems.

The resistive and piezoresistive transducers which measure dimensional variation within the mechanical system are called strain gages. Its operation is based on the change of electrical resistance within a conductor with respect to a change in a physical quantity. Typically, this quantity is length.[28]

There are two types of force / torque sensors under consideration. They are the:

1. Astek Model FS6-120A.
2. JR3 System

#### 28.1.1 Astek FS6-120A

This device is a six axis force/torque sensor which includes a transducer, strain gage, and instrumentation electronics needed to measure the six components of force that may be applied to the structure. The sensor is designed as a microprocessor which can resolve the six force components about any coordinate axis.[29] The sensor is easily adapted to an end effector and/or end effector tools.

#### 28.1.2 JR3 System

Another force and torque sensing system is the JR3 system. This equipment provides three, four, and six axis sensors. The JR3 sensor can accommodate a wide variety of robotic manipulators. Under normal ground conditions, the system is capable of sensing forces ranging from fifteen to five thousands pounds.[30]

### 28.2 Position Sensors

In addition to the force, torque, and tactile sensing instruments, TERMS must be able to define its position relative to the elevator, the Space Station, and other elements in the environment. There are two means by which position can be determined. The first involves the strategic positioning of a limited number of cameras capable of vision in all directions. Secondly, position transducers may be used to identify the position of an element relative to some reference frame.

There are two basic types of position transducers. These are potentiometers and optical encoders. A potentiometer converts a mechanical input, such as the position

of a variable terminal, into an electrical signal using a potential divider. The main advantages of potentiometers are low cost, small size, and versatility of operation. However, potentiometers do have some disadvantages. Potentiometers are analog devices and therefore require an analog-to-digital converter (ADC) to interface with a computer. The second disadvantage is that the variable (wiper) terminal is subject to mechanical wear.

Optical encoders are divided into two groups. These are absolute and incremental encoders. Both types transform the mechanical input quantity into an electrical output quantity by light absorption. The advantages of optical encoders are that they are very accurate (0.024%), and they are not subject to mechanical wear. Absolute position transducers are necessary when the control system is subject to frequent power cutoffs.[31]

The second method of position analysis is through the use of television cameras. NEC America, Inc. designs and manufactures industrial cameras specially suited for the users' needs. NEC produces a wide variety of camera sizes, all of which are lightweight and flexible. Designed to withstand the toughest environment, the cameras resist shock and magnetic distortion.[32]

Another positioning sensor that utilizes a television camera was developed at the Lyndon B. Johnson (LBJ) Space Center. This sensor is a triangulation system that measures the angle between two lines of sight to a point on an object, thereby determining the distance or position of the object. A helium/neon laser is used to reflect light off the object which is captured by a charged-coupled-device (CCD) camera.[32]

### 28.3 Proximity Sensors

The proximity of an object is the closeness of that object to a reference point. This parameter is of great importance to TERMS. The following proximity sensors were evaluated in this section for their operational feasibility.

1. Langley System
2. NASA System

#### 28.3.1 Langley System

An analog sensor was devised at the Langley Research Center that senses changes in proximity. The system was a line of limited-view light cells attached to logic circuits that keep track of the passing dark edges and that produce a

signal proportional to the change in location of the object. In essence, the sensor keeps track of the leading edge of the object.[30]

#### 28.3.2 NASA System

A second proximity sensor was researched at NASA's Jet Propulsion Laboratory. This system is similar in concept to the LBJ system discussed earlier. A light source (LED) and lenses are used to identify the position of the object and keep track of the object characteristics such as welds, rivots, and lines. The NASA sensor system is based on a simple array of optical proximity sensors that locate the edges of the object.[30] Either of these systems are feasible means for the proximity control of TERMS.

#### 28.4 Tactile Sensors

Being related to force transducers, tactile sensors are based on direct measurement transducers; that is, the transducer receives the applied force directly.

Tactile sensors are supported by two dimensional arrays of measuring cells. The sensors measure the contact pressure between the object surface and the robot end effector tool. Several different types of tactile sensors are based on conductive rubber, force-switchable diodes, or piezoresistive compounds.

A force transducer using a conductive silicone rubber is an effective touch-sensing instrument. This device measures the changing electrical resistance between an electrode and a conductive silicone rubber element as the two are forced together. The sensor can be made in a matrix form to cover an area for a single sensitive point.

To accommodate TERMS, a tactile system may be designed into an end effector gripping tool.[33] Sandia National Laboratories in Albuquerque, New Mexico have successfully demonstrated that tactile sensors can be made small enough for use as sensitive fingertips on robotic hands.

The sensing area is 0.5 square inches. It has two hundred and fifty-six sensing elements arranged in a sixteen inch by sixteen inch array. It consists of unique resistors with resistance varying as a function of applied load. In a one "g" environment, the array can sense forces ranging from one ounce to approximately one thousand pounds.

The digital tactile sensor is contained in a compact compartment for ease of storage. The microcircuit scans the sensor array and provides a digital output.[33]

The Sensoflex tactile system also meets the requirements of TERMS. This tactile measuring device uses the same technology as the system previously mentioned. Sensoflex includes a low-profile tactile pad and an electrical interface device. The system provides data which can be used to determine many parameters to include gripping force, part position, and orientation. Using the conductive elastomer technology, the sensor yields an array of tactiles which are scanned on a row by column sequence.[32]

## Chapter 29. Libration Minimization

Librations as a result of a robotic manipulator in normal operation on the tethered elevator must be addressed and viewed as an important design consideration. Librations are oscillations of celestial bodies in orbit about another. The oscillations are viewed from the body being orbited. This issue is of importance because of the nature of work and studies performed on the Space Station.

Librations are functions of the system mass, stiffness, damping, as well as, the velocity and acceleration of the system.

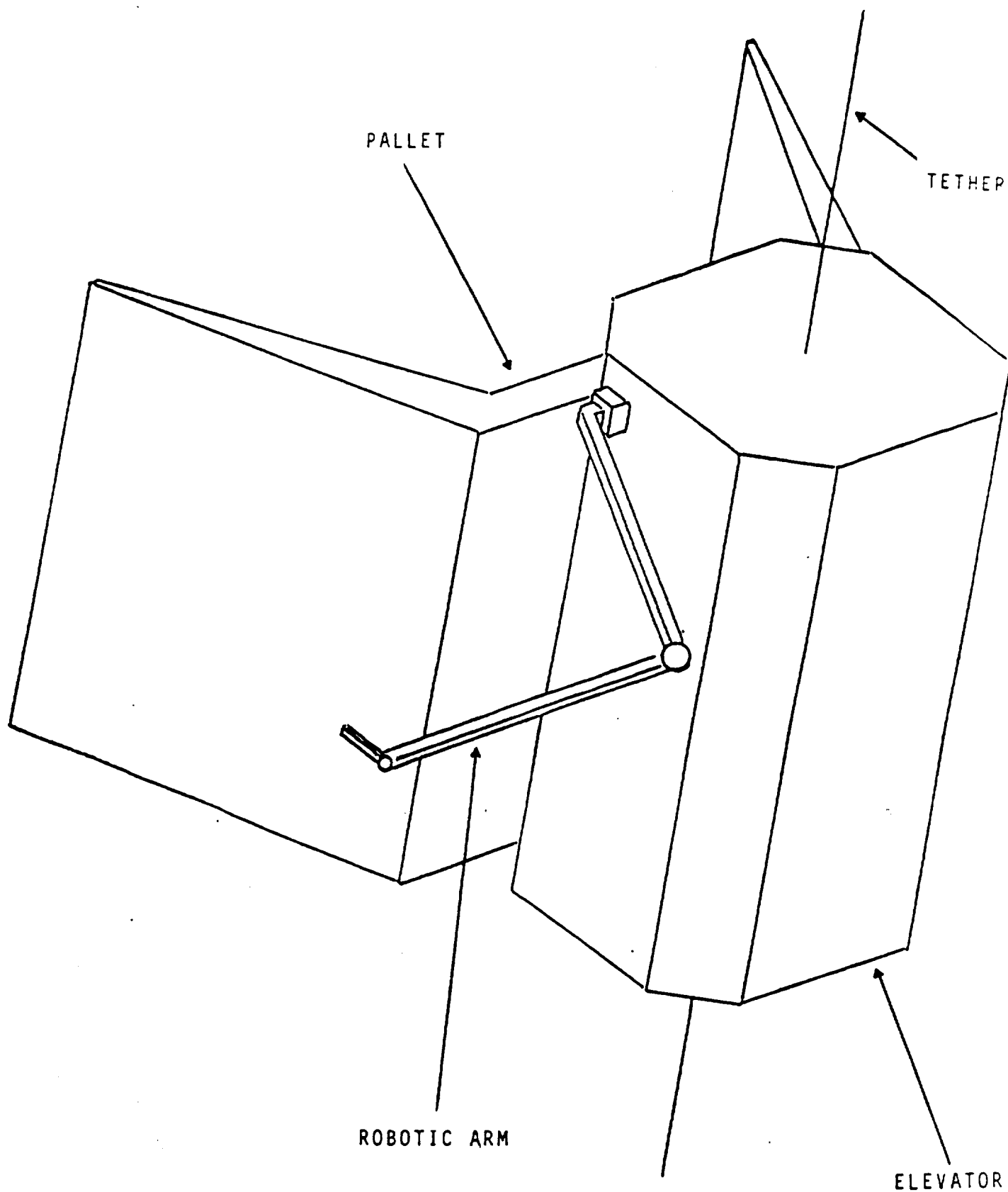
In Phase I, it was suggested that the manipulator arm to be employed on the tethered elevator should be the same arm used on the Orbiter. The manipulator arm used aboard the Orbiter is the Spar Aerospace arm.

The Spar Aerospace arm is fifty-one feet in length, jointed in three locations, possessing six degrees of freedom.

Though the exact effect this arm will have on the tethered elevator, in terms of librations, is not known, it was felt that they could be significantly reduced by proposing a more compact system.

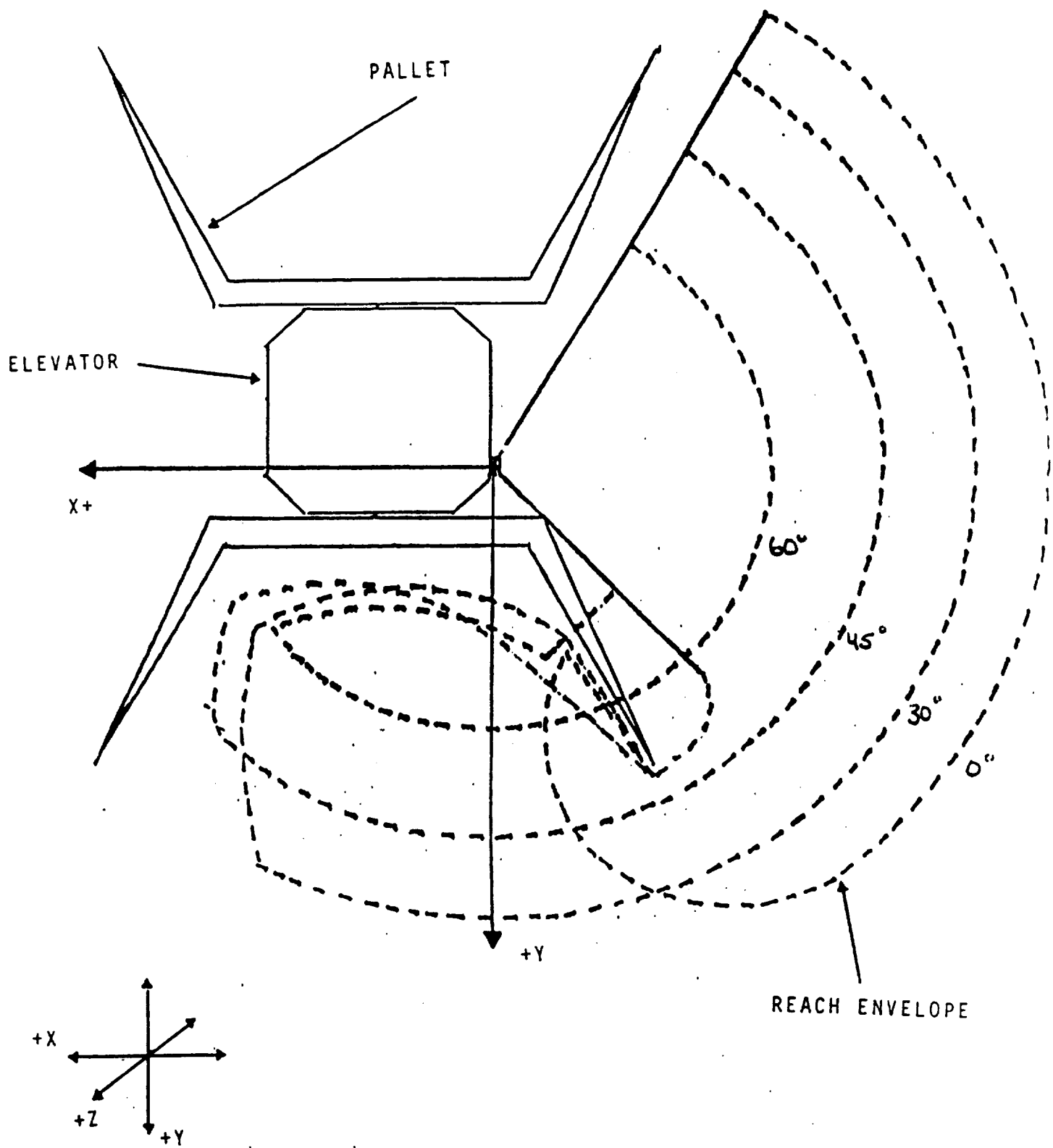
The compact system proposed (shown in Figure 2.22) is a two arm, diametrically positioned, scaled down version of the Spar Aerospace arm. Each arm will be approximately fifteen feet in length ( $1/3.5$  scale). As a result, the system's mass and mass moments would be greatly reduced. The forces that the arm generates on the elevator would be decreased. Torques and moments created would also be lessened by virtue of the arm's shorter length.

It is believed that this type of system will still possess the capability of servicing any portion of the elevator, as well as, payloads. Figure 2.23 shows the top view reach envelope of one of the RMS arms. The zero degree arc is associated with the arm moving strictly in the x,y



*ISOMETRIC VIEW OF TERMS*

Figure 2.22



*REACH ENVELOPE OF RMS (Top View)*

Figure 2.23

plane (no z-component). The sixty degree arc is associated with the arm moving with an inclination of sixty degrees with respect to the x,y plane.

Figure 2.24 shows the side view reach envelope of the same arm. The zero degree arc translates to motion strictly in the y,z plane. The sixty degree arc is due to motion inclined sixty degrees to the x-axis.

## Chapter 30. TERMS OPTIMAL SOLUTION - DESIGN PHASE II.

This chapter will present the optimal solutions as determined during Phase II of the design of TERMS. The following subsystems are:

1. Computer Hardware Systems
2. Data Transfer Devices
3. Control System Sensors
4. Libration Minimization

### 30.1 Computer Hardware Systems

The IBM AP-101 was chosen as the optimal solution among the computer hardware systems. Solution Matrix 2.8 contains the computer hardware systems that were evaluated.

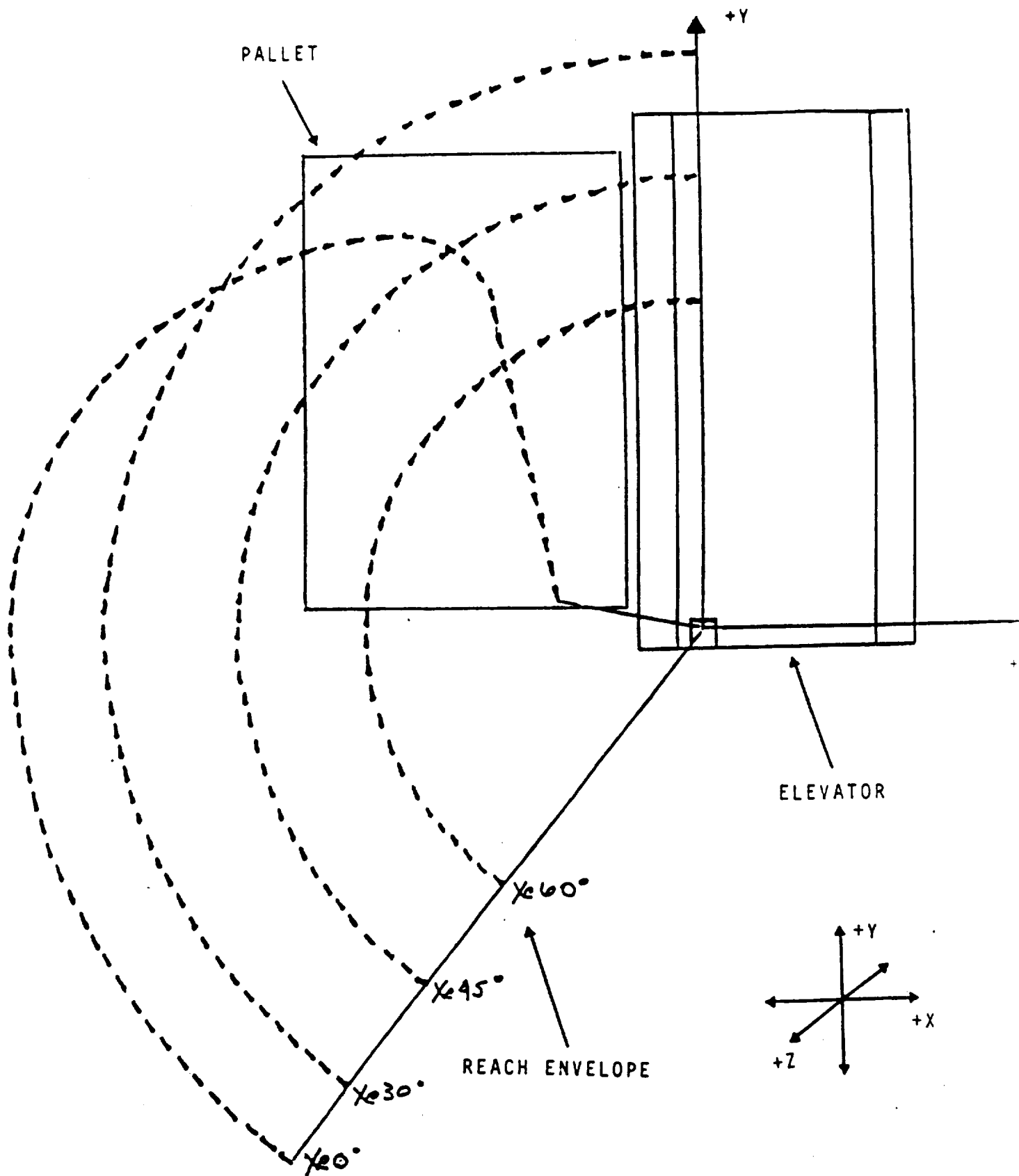
The primary reasons for the selection of the IBM AP-101 were physical dimensions, space worthiness, and reliability. Among the three alternatives, the IBM had the smallest dimensions (20"x9"x7"), allowing for the limited space available aboard the Space Station. The DEC VAX II and the Motorola 68000 series could not provide the compactness necessary to be employed on the Space Station.

The IBM also has proven space and TERMS related experience. Currently, five IBM AP-101's are employed aboard each space shuttle, handling a variety of tasks such as manipulator operation. The DEC VAX II and the Motorola 68000 series could not compare to the worthiness of the IBM AP-101, owing to the remarkable record of the IBM's on board the shuttles.

The IBM AP-101 has provisions for a ninety-five percent detection rate of hardware failure which could effect computer operation. With this capability, the IBM AP-101 provides a large degree of reliability. Upon detection of hardware failures aboard the Shuttle, the IBM immediately switches to a backup unit.

Additionally, the cost of employing the IBM AP-101 for use on TERMS would be considerably less than either the DEC





*REACH ENVELOPE OF RMS (Side View)*

Figure 2.24

VAX II or the Motorola 68000 series primarily because the Motorola 68000 and the DEC VAX II would need additional costs to do research and design in order to accommodate for the limited room aboard the Space Station.

### 30.2 Data Transfer Devices

Packet radio data transmission has been chosen as the optimal solution for a data link between the Space Station and the tethered elevator. Refer to Solution Matrix 2.9. The design considerations which allowed radio communication to surpass the other alternatives are wireless capability and transmission rate capability.

Wide-bandwidth laser beam transmission was deemed inappropriate since the provision for very high frequency beams carrying high volumes of data is not necessary. Optical and coaxial lines were determined as unacceptable means of data transmission due to the need for mechanical devices required to alter the range of transmission as the elevator traverses the tether. Thus, the radio transmission option offers the most feasible means as the data link for the control of TERMS.

### 30.3 Control System Sensors

In this chapter, the optimal choice for the following control sensor categories will be presented.

1. Force / Torque
2. Position
3. Proximity
4. Tactile

#### 30.3.1 Force / Torque

Referring to the Solution Matrix 2.10, there are two force / torque sensors under careful consideration. The Astek Model FS6-120A and the JR3 System.

The Astek FS6-120A six-axis force / torque sensor is an integrated measuring instrument which includes a transducer, strain gage, and instrumentation electronics necessary to measure the six components of force that may be applied to a structure. The second, JR3 system, provides three, four, and six axis sensors. Both systems possess suitable characteristics that would provide accurate and reliable information to the user. However, the Astek model proved to be the better system.

The Astek model can attach itself directly between the end effector and the end effector tool, making the Astek sensor simple, easily serviceable, and compatible with existing designs. The FS6-120A software system is designed to interact with either a stand-alone CRT terminal or a computer input/output port. In either case, the on board processor interprets a simple American Standard Code for Information Interchange (ASCII) command set, allowing the user to set the various sensor operation parameters and control the data output stream. Data output is available in a number of formats, including an ASCII output format and a more compressed 16-byte binary format. Also available are separate terminals for analog data and overlimit signaling.

### 30.3.2 Position

The Solution Matrix 2.11 shows the four types of position sensors systems investigated. There are two means by which position can be determined that are emphasized. The first involves the strategic positioning of a limited number of cameras capable of vision in all directions. This includes the NEC system and the Lyndon B. Johnson Space Center (LBJ) system. Secondly, position transducers may be used to identify the position of an element relative to some reference frame. There are two basic types of position transducers. These are potentiometers and optical encoders.

Of the four systems, the LBJ system was least favorable. The design parameters used in the determination of this were its high cost, large size, low factor of serviceability, power requirements, and complexity.

Running third were potentiometers. The advantage of potentiometers are their low cost, small size, and versatility. Unfortunately, potentiometers require an ADC to interface with a computer which may require additional space and power. Potentiometers are also subject to mechanical wear. As a result, the disadvantages of potentiometers, to include a lack of durability, simplicity, reliability, and interfaceability, outweighed their advantages.

Optical encoders and the NEC system ran a very close first and second. The design parameters that benefit optical encoders are their cost, operational performance, durability, and size. A factor that benefits optical encoders over potentiometers is that they are also slowly replacing potentiometers in those position measuring applications which require very long operational life.

The NEC system benefits from its simplicity, power requirements, and serviceability. These two systems ran very close in the decision matrix and profit from two different

technologies; hence, an incorporation of both systems would provide an optimal solution.

#### 30.3.3 Proximity

The two proximity systems researched are the Langley system and the NASA system. (Solution Matrix 2.12) Both systems are similar in concept. A light source and lenses are used to identify the proximity of an object and keep track of the object's characteristics such as welds, rivots, and lines.

The deciding parameters that favored the Langley system over the NASA system are its cost, interfaceability, serviceability, and simplicity. The model analog position sensor is easily set up or relocated and is inexpensive.

While motivated by the requirements for large space structures and possessing the ability to present output data in digital or analog form, the interfaceability of the Langley system ranked high when compared to NASA's.

#### 30.3.4 Tactile

The Sandia National Laboratory (SNL) system and the Sensoflex system comprise the two tactile systems under consideration. Refer to Solution Matrix 2.13.

Demonstrating that tactile sensors can be made small enough (0.5 square inches) for use as sensitive fingertips, the SNL system is ideal for small areas such as robotic hands. The most appealing characteristic of the SNL system is its incredibly small size. However, given the overall dimensions of the equipment that TERMS will handle and the design of the standard snare end effector, this design parameter does not compliment the system's simplicity and serviceability. As a result, the Sensoflex system is the optimum choice. The tactile system must be durable, simple, and easily serviceable, giving a slight advantage to the Sensoflex system.

#### 30.4 Libration Minimization

The technique described in Chapter 29 is believed to provide for reducing possible adverse effects of arm operation on the elevator. Refer to Chapter 29 for details.

### SECTION III.

#### TETHERED ELEVATOR CAPTURE AND DRIVE MECHANISM

- |                             |   |  |
|-----------------------------|---|--|
| <u>DESIGN PHASE I.</u>      | * | Drive Mechanism                            |
|                             | * | Hook / Unhook System                       |
| <br><u>DESIGN PHASE II.</u> | * | Hook / Unhook System                       |
|                             | * | Drive Mechanism                            |
|                             | * | Sliding Block / Friction<br>Belt Interface |
|                             | * | Braking Mechanism                          |
|                             | * | Materials                                  |

### SECTION III. TETHERED ELEVATOR CAPTURE AND DRIVE MECHANISM

#### INTRODUCTION

With tethers and the tethered elevator on the leading edge of space technology, many questions remain unanswered. The goal of this section is to provide insight into two specific areas of a tethered elevator system. The first problem area being the elevator drive mechanism and the second being the hook / unhook system. The applicability of the tethered elevator system depends greatly upon a multifaceted drive mechanism. The drive mechanism must not only propel the elevator along the tether, but must also help maintain stability, provide precise multi-speed capability and insure reliable long-term service in the microgravity environment of space. The other area that must be addressed is the hook / unhook system which securely fastens the elevator and its cargo to an extended tether.

In order to meet the requirements of the tethered elevator system, a drive mechanism must be designed that provides mobility to the system. The drive mechanism must be adaptable for both long distance, relatively high speed transportation and precise multi-speed maneuvers.[34] The drive mechanism must also exhibit durability in the microgravity environment of low Earth orbit.

The majority of the elevator's use will be long distance transport. This will require that the drive mechanism propel the elevator at a relatively high velocity across the length of the tether in a minimal amount of time. It has been suggested that the elevator travel at a maximum velocity of 5 meters per second.[35] At this velocity the elevator will require approximately 2.0 hours to traverse a 10 kilometer length of tether. Ideally, the drive mechanism will propel the elevator with no damage to the tether.

Many of the experiments and cargo that will be transported by the elevator require an undisturbed, microgravity environment during transportation. It is therefore necessary that the drive mechanism accelerate and decelerate smoothly to avoid affecting the payload.[36] Once the elevator has obtained the desired velocity, it is essential that the elevator maintain this velocity for extended periods of time as the elevator traverses the tether.

Although the concept of the drive mechanism is simple in nature, its purpose is most valuable. Without a properly functioning drive mechanism, the elevator would be stranded. It is essential that the drive mechanism be fully integrated with the elevator, yet easy to replace. Ideally, the drive

mechanism should be a self-contained unit that could, if necessary, be replaced as a whole.

The drive mechanism must be designed to both accelerate and decelerate the elevator along the entire length of the tether. For example, if the gravitational and centrifugal forces that the elevator will encounter as it traverses a tether necessitate the use of an integrated braking system. The braking system would be used to help slow the elevator during periods of acceleration due to gravity and centrifugal forces and also to make docking procedures at the Space Station and end masses much easier.

In conjunction with the drive mechanism, the task of designing an effective method of hooking and unhooking the elevator from an extended tether must be addressed. The hook / unhook system must be designed to attach to a variety of tethers. The elevator will be attached and detached to an extended tether by using the remote manipulator system.[34] All extravehicular activities are to be avoided in all hooking and unhooking operations.

## DESIGN PHASE I. TETHERED ELEVATOR CAPTURE AND DRIVE MECHANISM

### Chapter 31. DRIVE MECHANISM

The following drive mechanism systems were studied for their operational feasibility in conjunction with the tethered elevator:

1. Friction Belt
2. Friction Wheel
3. Spool Type
4. Robotic
5. Electromagnetic
6. Gas Systems

#### 31.1 Friction Belt

The friction belt category of the drive mechanism has three sub-categories that include:

1. Tri-Wheel Friction Belt
2. Bi-Wheel Friction Belt
3. Quad-Wheel Friction Belt

Each of these sub-categories shall be explained with advantages and disadvantages of each given.

##### 31.1.1 Tri-Wheel Friction Belt

The tri-wheel friction belt utilizes three wheels and one toothed friction belt on each side of the tether. An example of a tri-wheel friction belt is shown in Figure 3.1. In this system, only one friction belt is driven. This friction belt is rotated by a small electric motor that induces rotational energy into the friction belt.[37] This rotational energy is transmitted to the other friction belt through constant pressure supplied by the linear actuator and the sliding blocks. The friction belts are placed in contact with the tether along the straight section of the belt. The friction belts are forced together with the tether between them producing a uniform surface of contact between the tether and the friction belts. The rotational velocity of the friction belt is transformed to linear motion of the drive mechanism along the tether.

The friction wheels used in this system are 30 mm in radius and are covered along the outside edge with a friction rubber material to insure a good grip of the belt.[37] The friction belt is driven by the outermost pulley of the three pulley system. The drive wheel is powered by a small D.C.



# TRI-WHEEL FRICTION BELT DRIVE MECHANISM

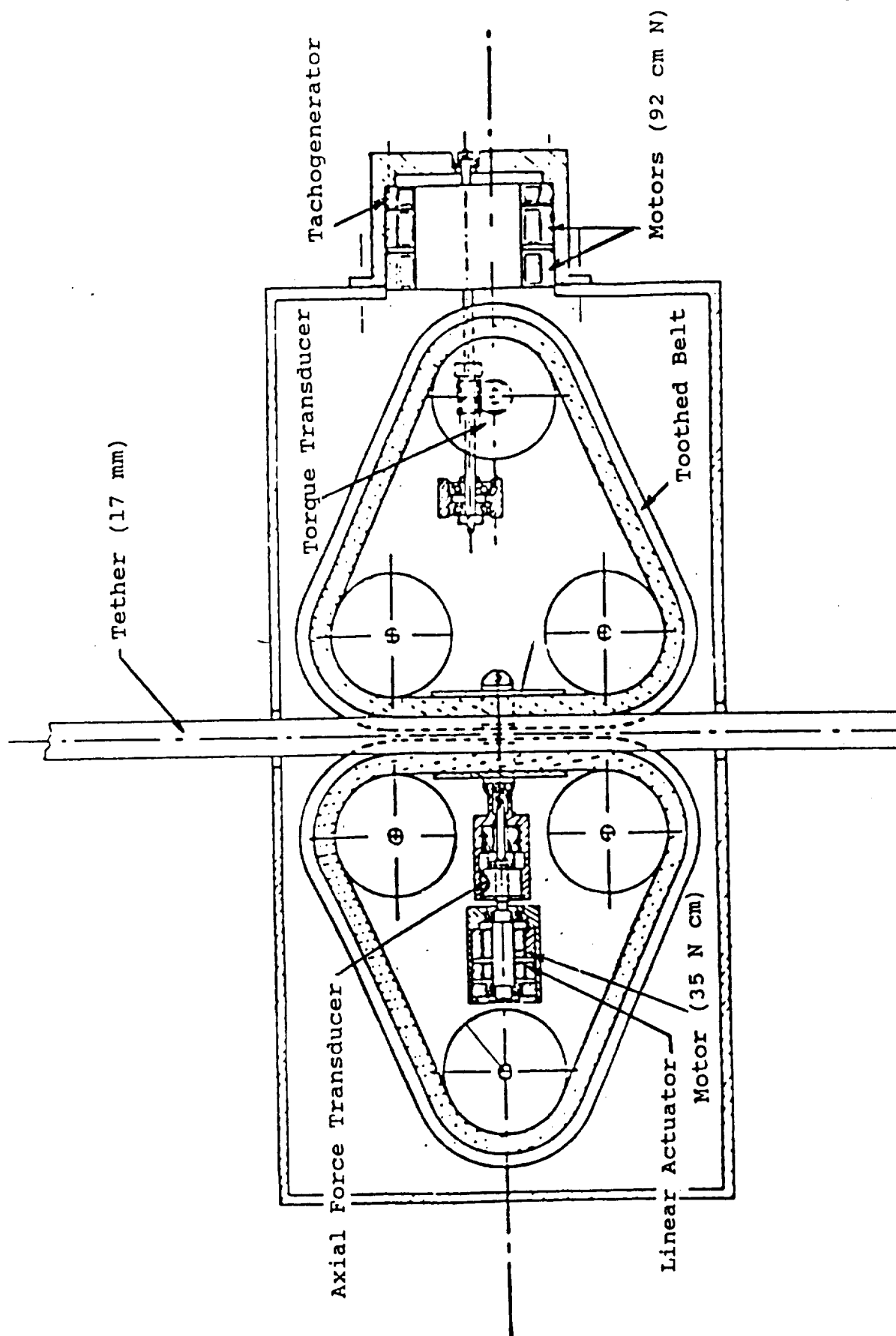


Figure 3.1

brushed torque motor.[37]

The output of the electric motor is transmitted through a tachogenerator that measures the rotational speed that will be delivered to the drive wheel. By monitoring the rotational speed of the drive wheel the tachogenerator will help to prevent slippage between the drive wheel and the friction belt. A single synchronous brushless torque motor with redundant windings for redundancy could be used instead of the tachogenerator.[37] A gear coupling of worm and worm gear type will also be utilized on the output of the drive motor to insure irreversibility of the belt and pulley rotation.[37]

The friction belt used in this design is a posidrive or metal tape belt made of Neoprene with teeth covered by nylon.[37] The friction belt is internally reinforced by metallic cables. To insure good contact between the belts and tether, sliding blocks are utilized.

The sliding blocks are controlled by a linear actuator. The linear actuator is powered by two small D.C. brushless motors (one is for redundancy).[37] The linear actuators and sliding blocks make it possible to apply both pressure to the friction belts and tether and also to separate the friction belts far enough to allow for hooking and unhooking operations. To prevent excessive damage to the friction belts, small bearings or needles will be used on the friction belt contact surfaces of the sliding blocks.

The hook / unhook procedure that will be used for the tri-wheel friction belt design consideration is very simple. First, the remote manipulator system will attach to the elevator. Once the arm is attached to the elevator, the linear actuator will pull the sliding blocks away from the tether thus disengaging the friction belts from the tether. Then, guides that control the position of the tether in relation to the friction belt contact surface will also be released. The tether is now free to be removed from the space between the belts. The remote manipulator system will now remove the elevator and drive mechanism from the tether.

The main advantage of this design is a low number of belt rotations per increment of tether length traversed. The resulting disadvantage is the overall volume of the drive mechanism.

### 31.1.2 Bi-Wheel Friction Belt

This system, shown in Figure 3.2, is very similar to the tri-wheel friction belt system that was previously discussed. The bi-wheel friction belt utilizes two friction wheels and

# BI-WHEEL FRICTION BELT DRIVE MECHANISM

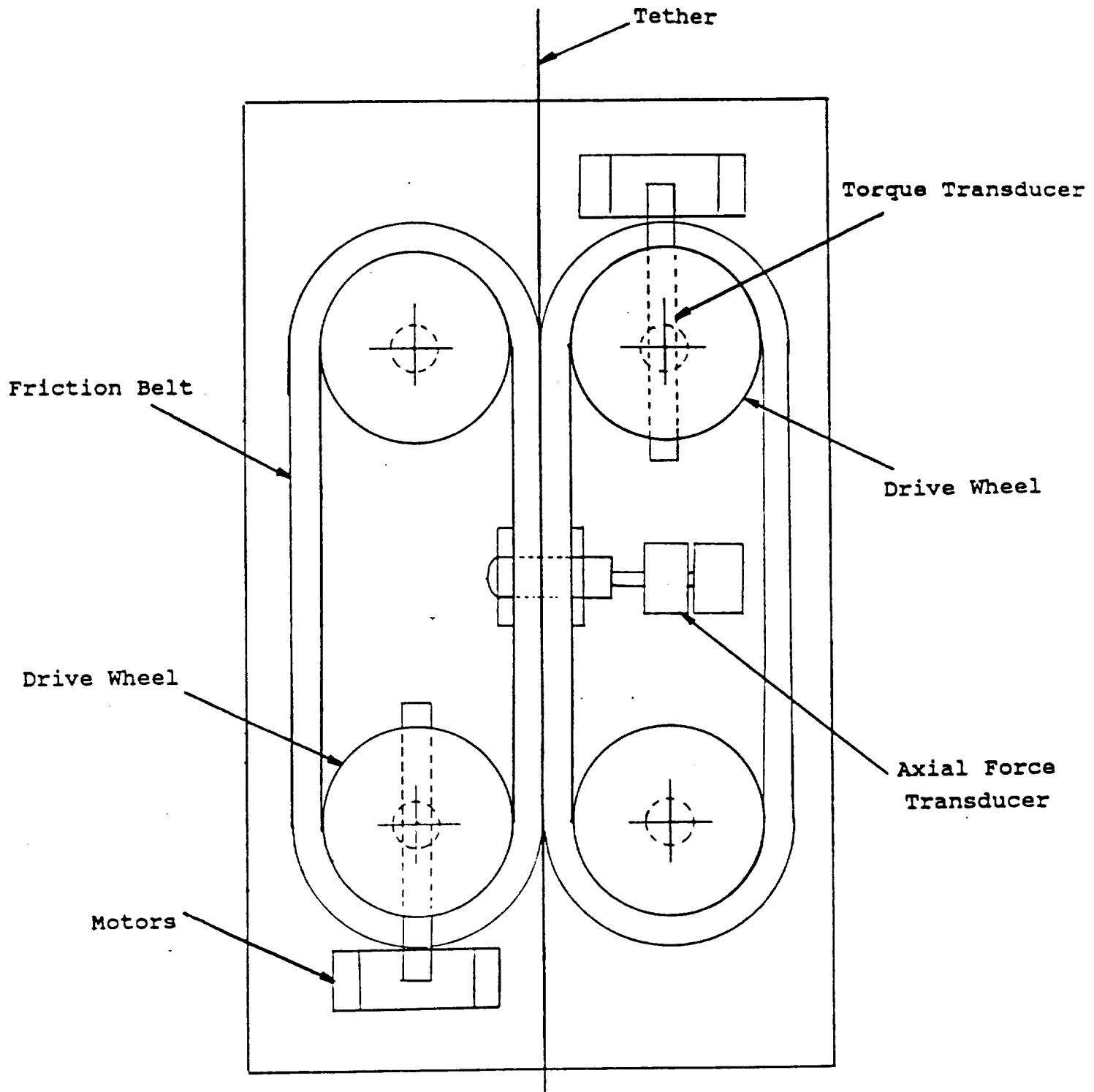


Figure 3.2

one toothed friction belt on each side of the tether. The system uses friction wheels that are 40 mm in radius.

The operation and hook / unhook procedures for this system are identical to those of the previously mentioned design. The belt type and linear actuator motor sizes are also the same.

The main advantage of this system is that it is lighter and smaller than the tri-wheel design. The main disadvantage is that the friction belts will have greater wear due to the higher number of belt rotations required to traverse each increment of tether length.

#### 31.1.3 Quad-Wheel Friction Belt

The quad-wheel friction belt, shown in Figure 3.3, is similar to the friction belt systems that have already been discussed. The quad-wheel friction belt utilizes four friction wheels and one toothed friction belt on each side of the tether. This system uses friction wheels that are 25 mm in radius.

The operation and hook / unhook procedures for this system are identical to those of the previously mentioned designs. The belt type and motor sizes are also the same.

The main advantage of this system is that there would be less belt wear due to the increase in friction belt length. The main disadvantage of the system is the increased weight and size of the system.

### 31.2 Friction Wheel

The friction wheel category of the drive mechanism consists of five designs. These are:

1. Dual Friction Wheel
2. Tri-Friction Wheel
3. Multi-Wheel
4. Triad Friction Wheel
5. Idler / Pulley

All five drive mechanisms operate on the same principle. A rotating friction wheel or wheels contact the tether, propelling the elevator.

#### 31.2.1 Dual Friction Wheel

The dual friction wheel system, shown in Figure 3.4, consists of two friction wheels and one electric motor. One

# QUAD-WHEEL FRICTION BELT DRIVE MECHANISM

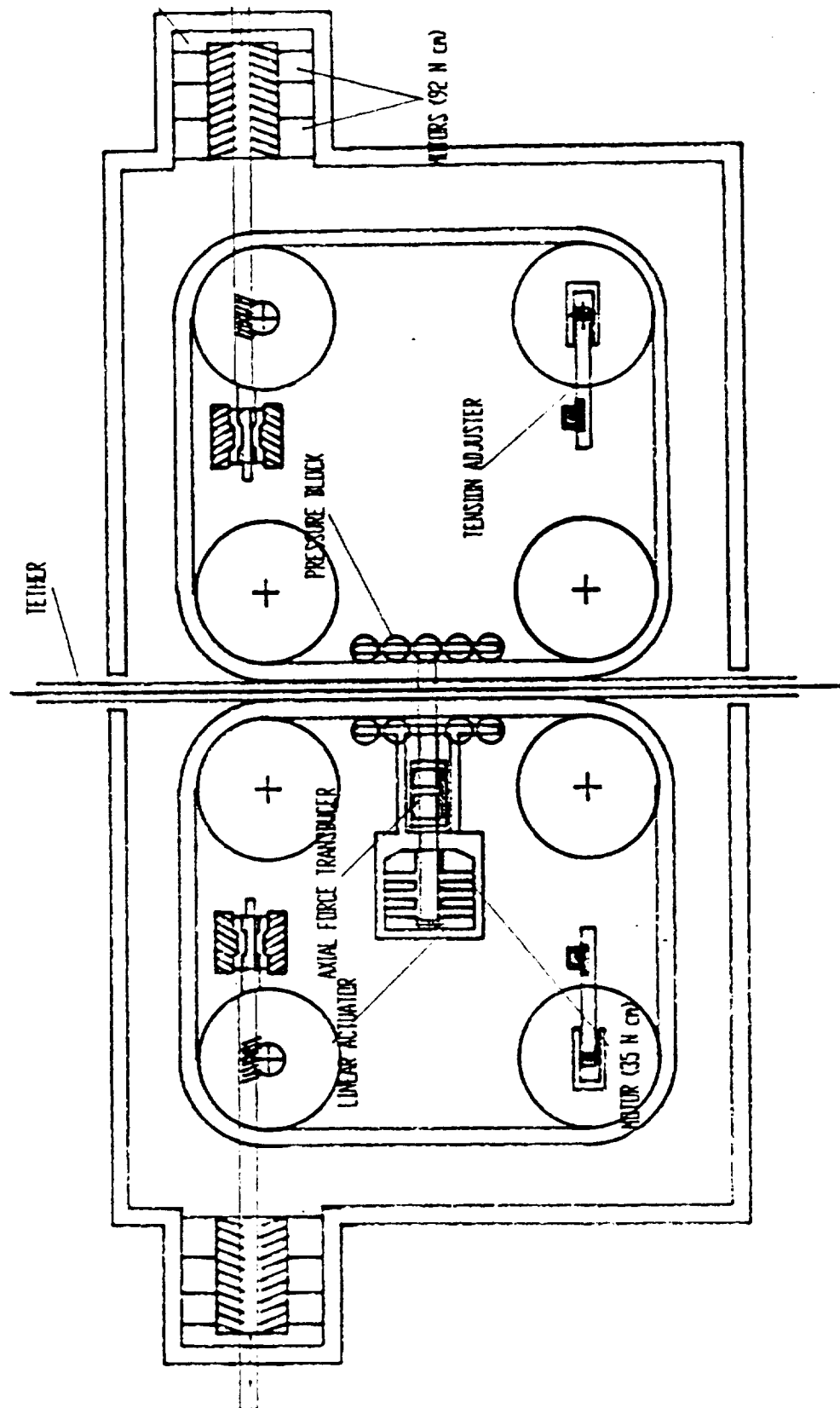


Figure 3.3

# DUAL FRICTION WHEEL DRIVE MECHANISM

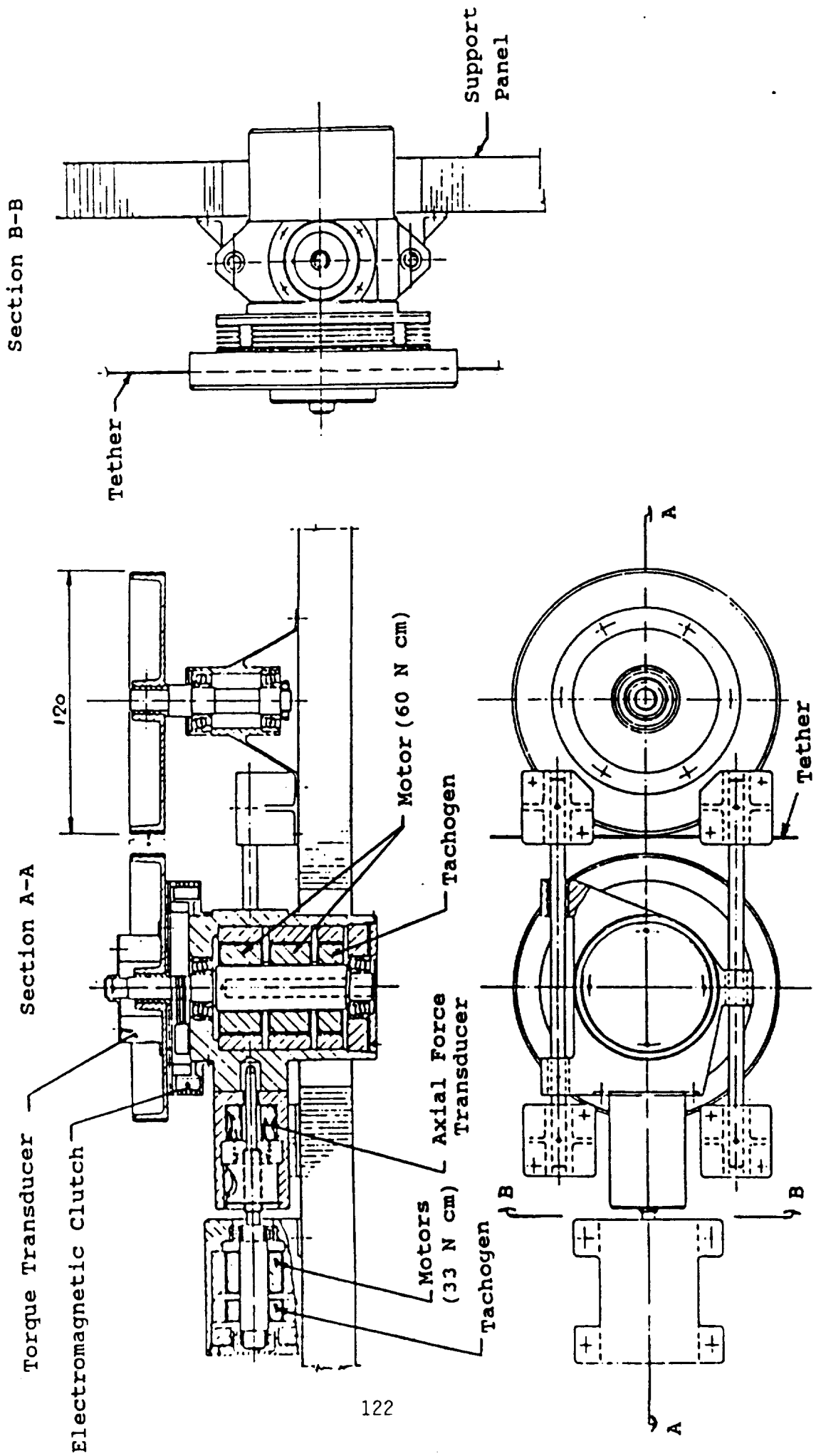


Figure 3.4

of the motors is driven while the other is idle. The tether is pushed or pulled between the two rotating wheels.

The drive wheel is powered by two brushed D.C. torque motors. One of the motors is for redundancy. An electrodynamic clutch is mounted on the drive wheel to stop its rotation when the elevator is in the braked or stopped position.

A linear actuator fixed to the main structure moves the drive wheel against the idle wheel during operation. In this position, the tether is firmly held between the two wheels. Both of the rotating wheels are covered with a high friction rubber material along the outer edge. The linear actuator is powered by two brushed D.C. torque motors.[37] One of these motors serves as a backup for the other. The linear actuator retracts the drive wheel creating a space between the wheels for hooking and unhooking operations. A spring between the actuator and wheel support reduces the transmission of sudden loads.

The second wheel receives no electric power and is mounted on a bracket fixed to the frame of the drive mechanism. It is only active when the drive wheel is engaged by the linear actuator.

A tachogenerator is used to control the angular velocity of the drive wheel. A torque transducer monitors slipping between the tether and rotating wheels. If slipping occurs, the torque transducer will detect it and signal the linear actuator to increase the pressure of the drive wheel on the other friction wheel.

The procedure for hooking and unhooking the elevator with this drive mechanism is very simple. After the remote manipulator arm has been attached to the elevator, the linear actuator moves the drive wheel away from the idle wheel creating a space between the two tether contact surfaces. The guides used to properly position the tether between the drive wheels are then released and the elevator is pulled away from the tether.

One advantage of the dual friction configuration is the relative simplicity of the design. Another is its compact size. Tests have shown the size of the drive mechanism to be 130 mm X 130 mm X 360 mm.[37] The small size also helps to reduce the mass of the system.

The main disadvantage of the dual friction system is that the pressure on the tether is difficult to control. Too much pressure on the tether may result in tether damage, while not enough may result in slipping.

# TRI FRICTION WHEEL DRIVE MECHANISM

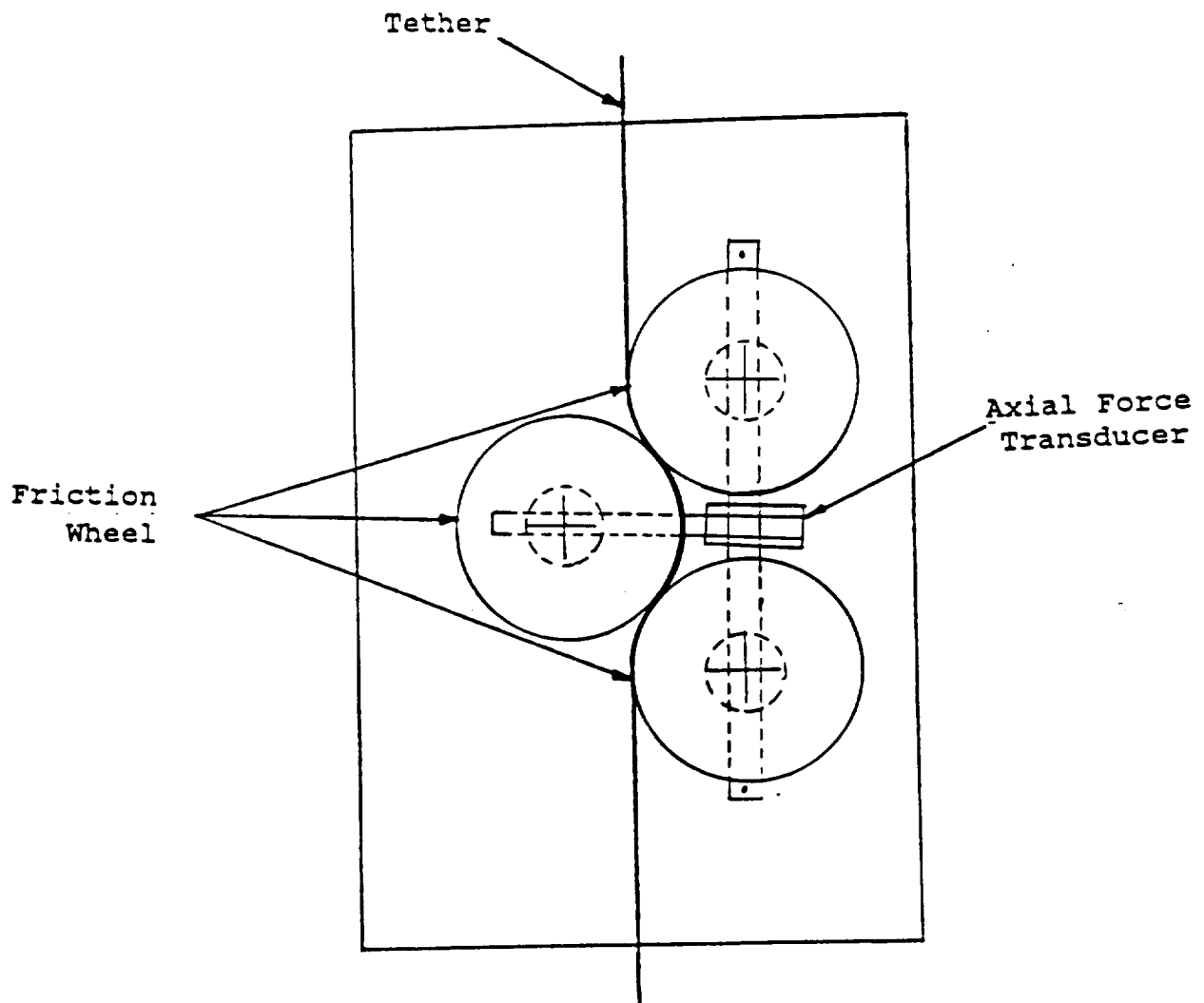


Figure 3.5



## MULTI FRICTION WHEEL DRIVE MECHANISM

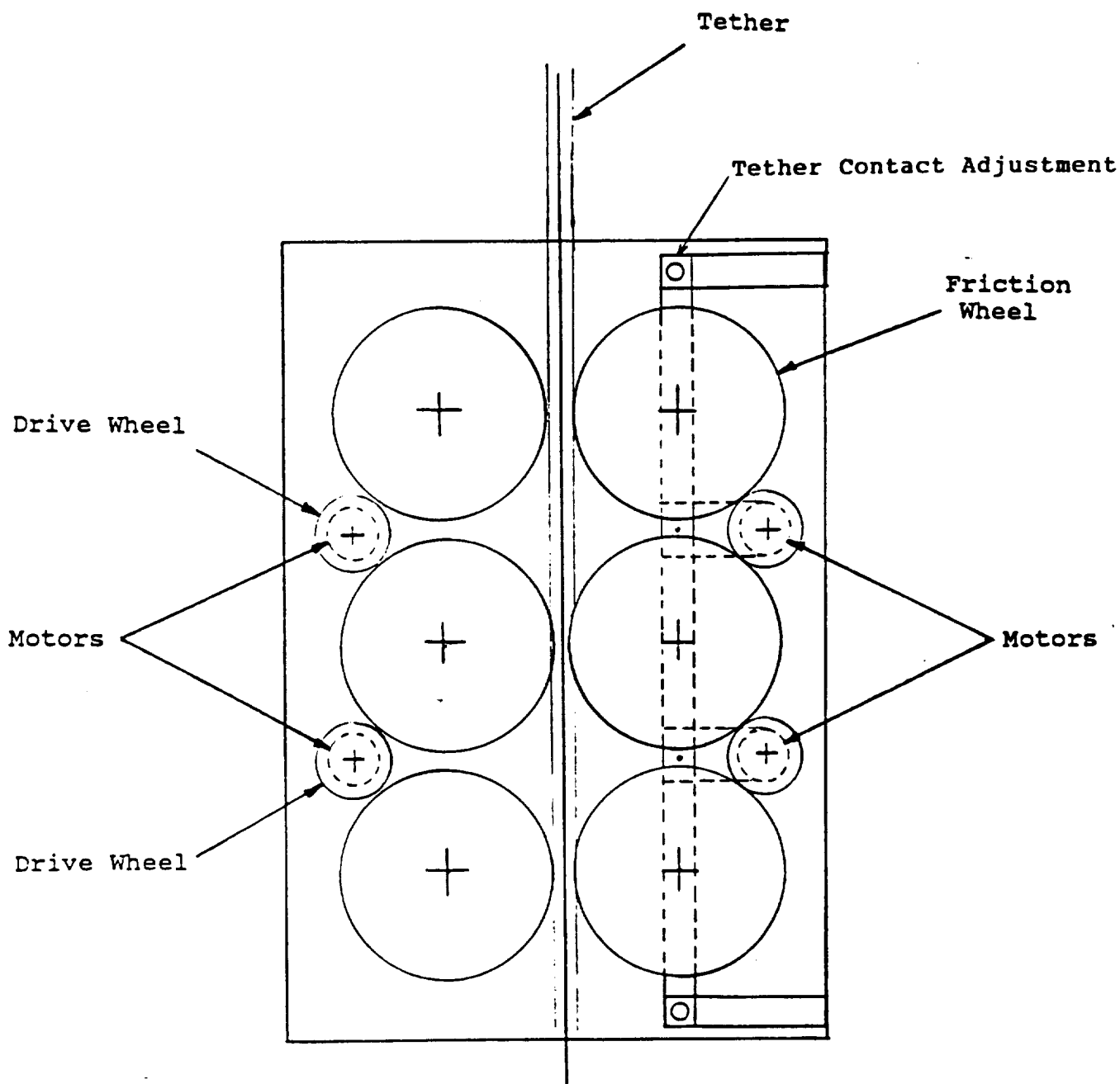


Figure 3.6

### 31.2.2 Tri-Friction Wheel

The tri-wheel friction drive mechanism, shown in Figure 3.5, is similar to the dual friction system already presented in that the tether passes between a series of friction wheels. This system consists of three planar wheels in contact with the tether.

The motor size, hook / unhook procedure, and use of a tachogenerator are all identical to the previously mentioned friction wheel design consideration.

One advantage of the tri-friction system is the increased tether contact surface area. Another advantage is that it is also a relatively simple design with few moving parts. The design is also comparatively compact and lightweight.

The major disadvantage of this drive mechanism is that slipping between the tether and wheels may occur if the contact pressure is not properly controlled. If too much pressure is applied to the tether, damage may result.

### 31.2.3 Multi-Friction Wheel

Figure 3.6 shows the multi-friction wheel system. The drive mechanism consists of six friction wheels in contact with the tether and four drive wheels. The tether is pulled along simultaneously by the six friction wheels. The six friction wheels increase the contact area between the friction wheels and the tether.

The multi-friction system is driven by four drive wheels each powered by a small D.C. electric torque motor. The four wheels are in constant contact with the six friction wheels. A tachogenerator and torque transducer are used in the same manner as on the other friction wheel designs.

The drive wheels are divided into two sets of three friction wheels each. The right set of three wheels is mounted on a crossbar that allows the three wheels and drive motors to move simultaneously. The motion of the crossbar is controlled by a set of linear actuators. For hooking and unhooking operations, the right set of friction wheels and drive motors is moved. This movement releases the pressure between the friction wheels and tether permitting hooking and unhooking operations.

The major advantage of this system is the increased contact between the tether and the friction wheels. Another advantage is the redundancy of the system.

The disadvantages of this system are its relatively large size and complexity. Due to the addition of extra wheels, the mass of the system is also greatly increased. Because the system consists of a multitude of moving parts, the probability of mechanical malfunction is increased.

#### 31.2.4 Triad Friction Wheel

The triad friction wheel drive mechanism, shown in Figure 3.7, has two independent drive mechanisms, one for translation and one for exact positioning. The two drive mechanisms are placed at opposite ends of the elevator to allow control of pitch and roll.[36] When one mechanism is engaged, the other is idle and serves as a guide.

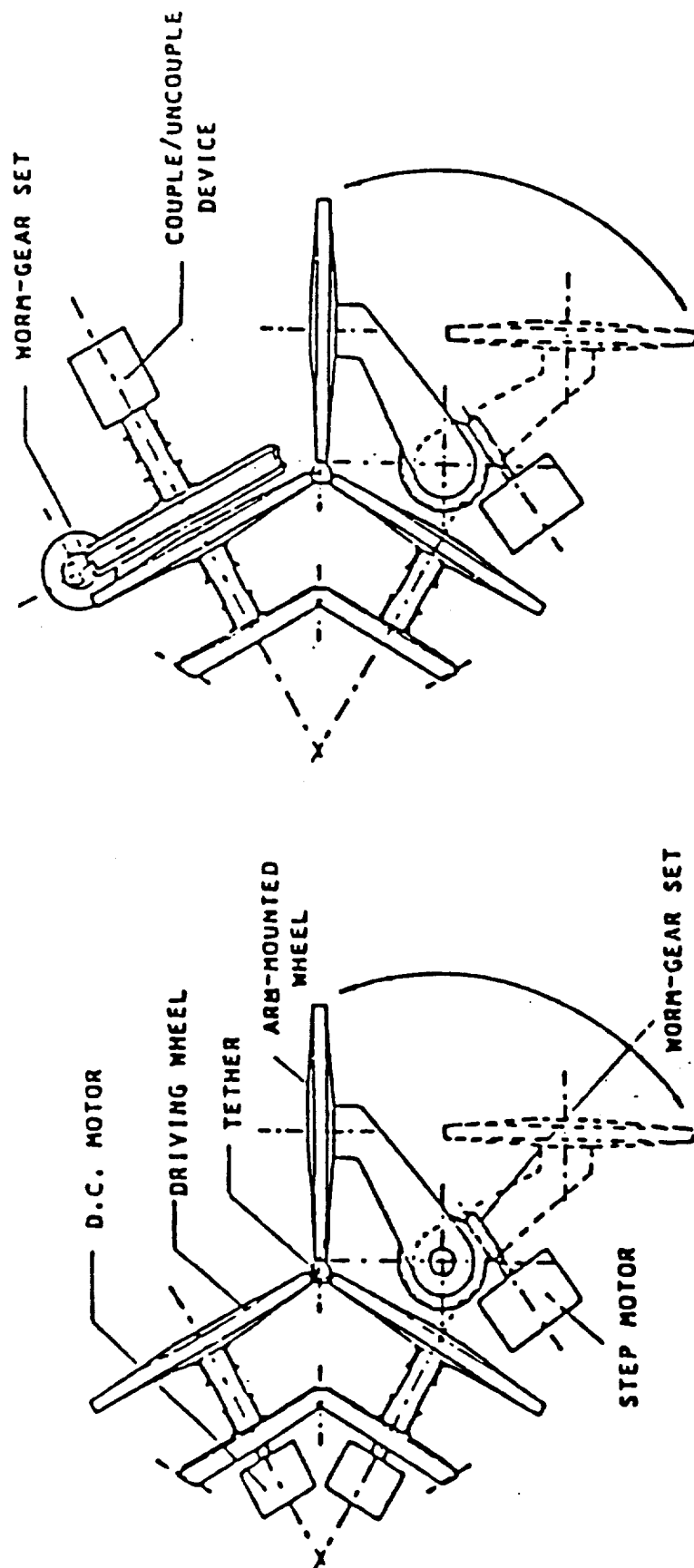
The translation drive mechanism (TDM) has the function of moving the elevator along the tether through long-distance maneuvers. The accurate displacement mechanism (ADM) has the function of producing very slow movements with high precision. The ADM also performs the final approach to the end mass or Space Station. In a microgravity application, the ADM executes the required motion profile after the elevator has reached the desired position along the tether. The ADM also keeps the elevator braked when the TDM is not operating.

Each drive mechanism is composed of three friction wheels positioned 120 degrees apart on center around the tether. Two of the friction wheels act as drive wheels. The TDM has two electric D.C. motors that act directly on the drive wheels, while the ADM has one electric motor which powers the two drive wheels simultaneously through a worm gear set.[36] On both drive mechanisms, the third friction wheel acts as a guide.[36] The third friction wheel rotates about the yaw axis of the tether by the operation of an electric step motor coupled with a worm gear set. The force induced by this wheel on the tether is equally distributed to the other two friction wheels, thus propelling the elevator along the tether.

The control system uses accelerometers to determine position along the tether. Other sensors measure the velocity of the wheels and the pressure of the wheels on the tether. A tachogenerator is used to control the angular velocity of the drive wheel.

The procedure used for hooking and unhooking the elevator with the triad friction wheel drive mechanism is relatively simple. First, the manipulator arm will attach itself to the elevator. Then the third wheel of the drive mechanism will be rotated away from the tether. The guides will then be released on the other drive mechanism and the arm will pull the elevator away from the extended tether.

# TRIAD FRICTION WHEEL DRIVE MECHANISM



ACCURATE DISPLACEMENT MECHANISM

TRANSFER DRIVE MECHANISM

Figure 3.7

There are two disadvantages to this system. First, slippage of the tether between the drive wheels cannot be avoided due to the difficulty of gripping a 3 mm diameter tether with three friction wheels. Second, damage to the tether will result if the pressure force of the wheels on the tether is not carefully controlled.

The only advantage of this system is that it has the ability to move precisely along the tether during variable velocity operations due to the independent ADM system.

#### 31.2.5 Idler / Pulley

The final design consideration of the friction wheel type is the idler / pulley drive mechanism. This system consists of an independent drive wheel that is attached to the elevator, an idler pulley and a friction belt.

The idler / pulley system is shown in Figure 3.8. The drive wheel is powered by a brushed D.C. electric motor.[38] The drive wheel is covered with a high friction material such as rubber along the outer surface to insure good contact with the tether and belt.

The friction belt is a toothed posi-drive belt made of Neoprene with teeth covered by nylon. The friction belt is internally reinforced with metallic cables. The friction belt and idler pulleys are attached to a swinging arm that is fixed to the elevator.[38]

The system has two positions. The first is the engaged position in which the idler pulley arm is rotated counterclockwise to obtain good contact with the drive wheel. The second position is the disengaged position. In this position, the idler pulley arm does not make contact with the drive wheel.

To engage the drive mechanism the tether is placed between the friction belt and the drive wheel by the rotation of the idler pulley arm. The tether is guided to the precise location by guides attached to the drive mechanism. Once a good contact between the tether, drive wheel, and idler pulley belt is achieved, the drive wheel is started.

A spring is also utilized in this design. The spring helps to absorb or dampen the vibrations of the idler pulley arm when it is engaged to the drive wheel.[38] The spring also aides in the retraction of the idler pulley arm to the disengaged position.

There are two disadvantages to this system. First, slippage between the tether and drive wheel will be hard to

# **IDLER / PULLEY FRICTION WHEEL DRIVE MECHANISM**

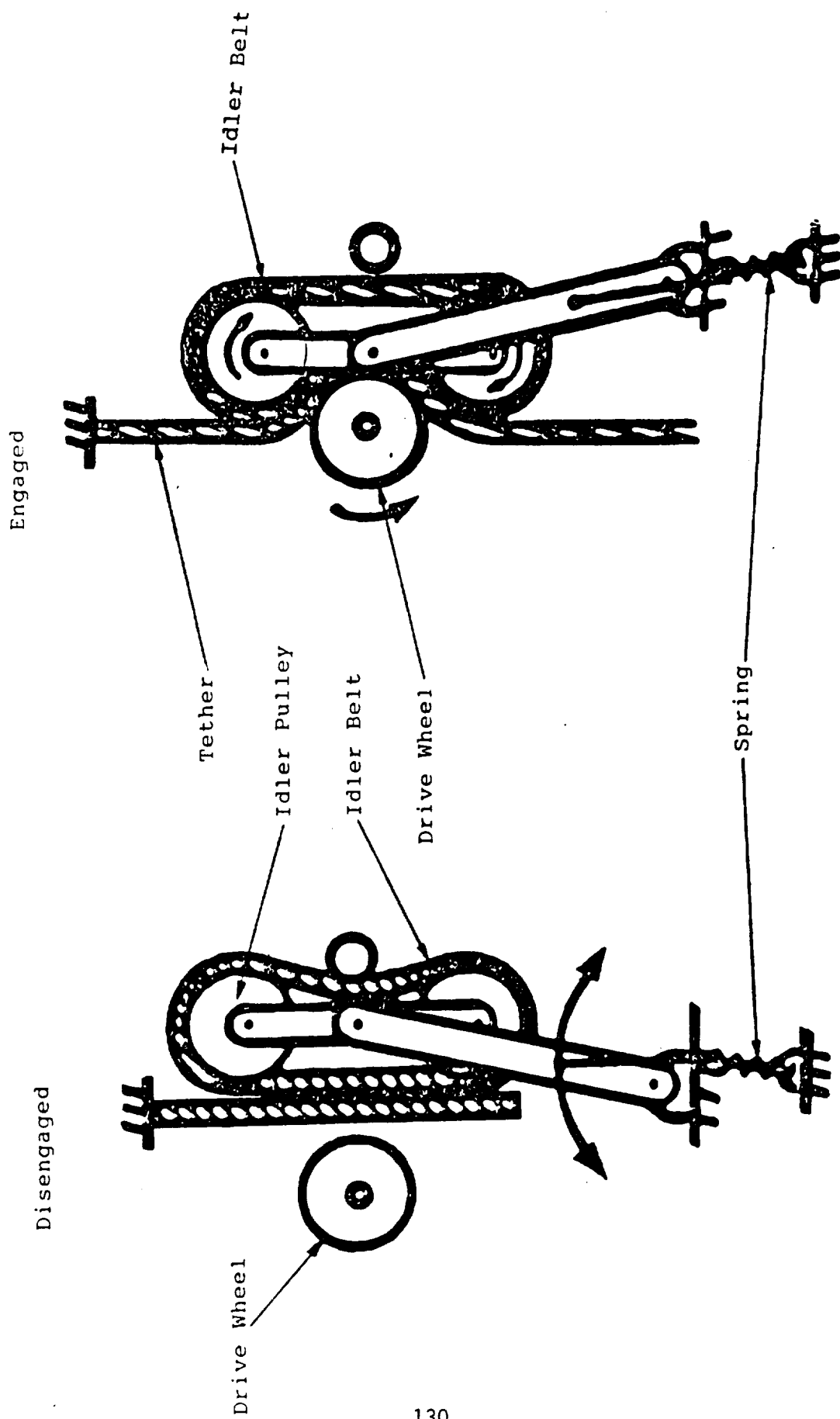


Figure 3.8

prevent. Excessive tether wear will also be a problem because a constant force cannot be applied to the idler arm. The lack of a constant force will allow slippage of the drive wheel on the tether causing damage or wear.

The main advantage of this system over some of the other systems considered in this section is the increased area of contact between the tether and drive wheel.

### 31.3 Spool Type

The next series of design considerations that were investigated were those of the spool type. Three spool type design variations are discussed, including:

1. Dual Spool Mono Tether.
2. Dual Spool Tri Tether.
3. Wrap Around Spool.

#### 31.3.1 Dual Spool Mono Tether

The dual spool mono type, shown in Figure 3.9, involves the use of one tether and two large spools or reels. One of the spools will be located on the Space Station and the other will be located on the end mass. The elevator will be attached to both ends of the tether and guided by the connecting length of tether between the two spools. A portion of the tether length will be wound once or twice around the spools at either the end mass or Space Station and will then be used to connect the two spools.

The rotation of the spools will either increase or decrease the distance between the spool and the elevator. For example, if the elevator were to travel from the Space Station to the end mass, the bottom spool would rotate clockwise while the top spool also rotated clockwise. In this way, the tether length between the elevator and Space Station becomes longer, and the tether length between the elevator and end mass becomes shorter.

The spools will be driven by two D.C. motors. One of these motors will be a part of the redundant or backup system. The motors shall be equipped with the proper gearing package to insure that the output speed of the motor is correct. The motors shall also be equipped with a locking crank mechanism. The locking crank is similar to that found on most boat trailers. The crank will be used to prevent backlash or backslip of the spool and tether. The spools will be constructed from a lightweight aluminum alloy or plastic with steel gears, center rod, and support connections.

# DUAL SPOOL MONO TETHER DRIVE MECHANISM

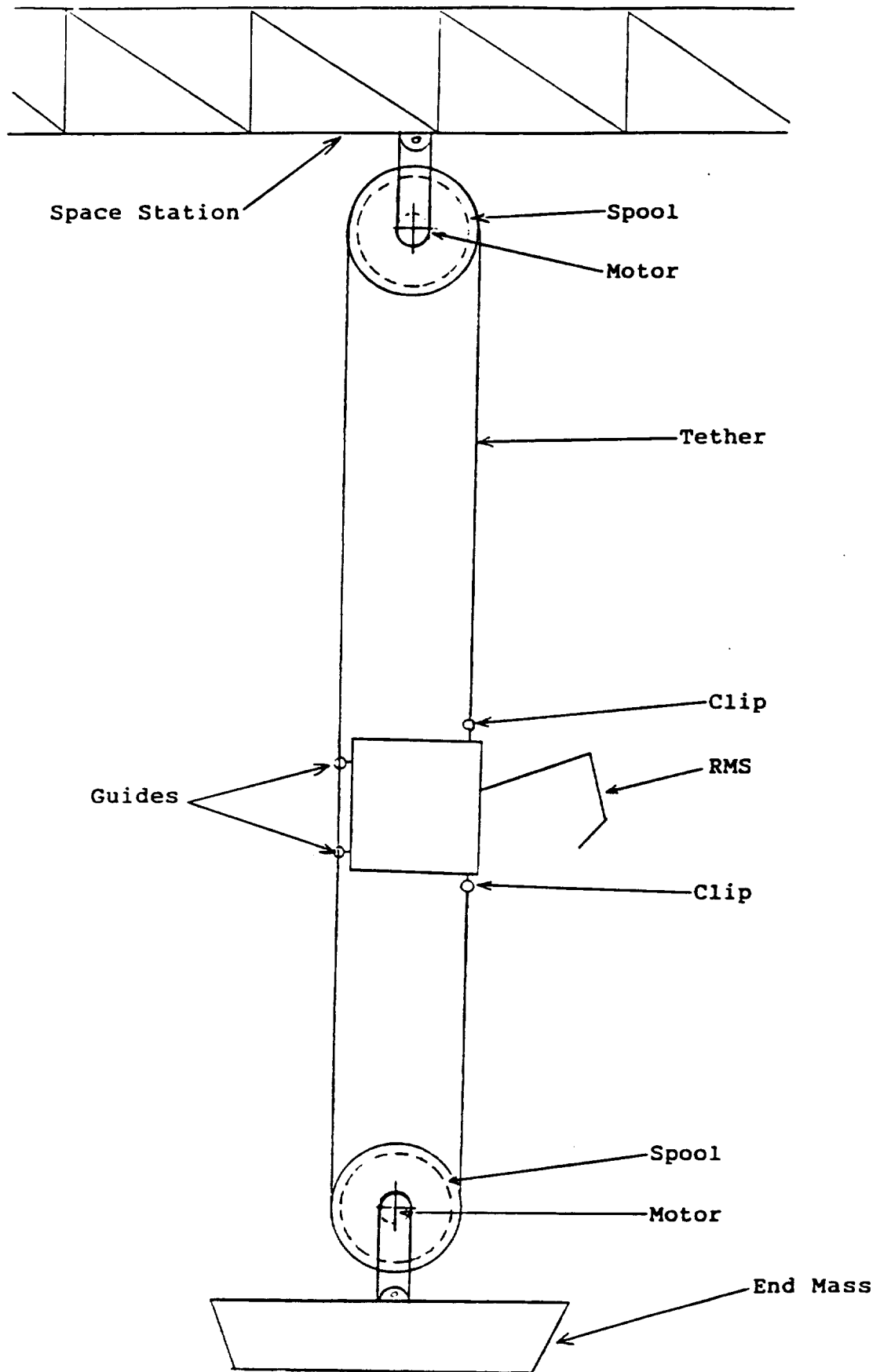


Figure 3.9  
132



To make hooking and unhooking operations easier the clips that attach the tether ends to the elevator will be remotely operated. The guides that will be used on the back side of the elevator will also be remotely operated to release the tether during elevator removal procedures. The mono tether device will also be equipped with a tether severing device to release the elevator in the case of an emergency.

The dual spool mono tether design has three main advantages. First, all of the mechanical equipment used to move the elevator is located on either the Space Station or the end mass. This provides for easier maintenance and repair of these components. Second, is its relative simplicity. Finally, with the mechanical hardware located on the Space Station and end mass, the elevator will have more cargo area.

There are several disadvantages associated with this design. First, the tether lengths that run parallel to each other may experience problems with tangling. Next, slippage may occur between the spools and tether. Finally, unhooking operations would require that the RMS connect the two loose tether ends to each other to prevent loss.

#### 31.3.2 Dual Spool Tri Tether

The next design consideration of the spool type is that of the dual spool tri tether. This configuration consists of three tether lengths and two large spools. Refer to Figure 3.10. This system is again simple in nature. As in the previously discussed design, one spool is mounted on the Space Station while the other is mounted on the end mass.

The basic concept behind the system is that as the elevator traverses an extended tether, one spool is pulling the elevator while the other is releasing tether to permit the travel. This involves two of the three tethers of the system. The third tether of the system is fixed between the Space Station and end mass. This permanent tether only serves as a guide as the elevator is pulled by the two powered tethers. Future modifications could use this tether as an umbilical for transporting power or communications between the Space Station and elevator.

The clips and guides that will be used on the elevator will be remotely controlled to simplify hooking and unhooking operations. To remove an elevator from an extended tether, first the two spool driven tethers must be detached from the elevator with the loose ends either being attached together or attached to the Space Station or end mass, whichever applies. After the manipulator arm is attached to the elevator, the guides for the permanent tether will be

# DUAL SPOOL TRI TETHER DRIVE MECHANISM

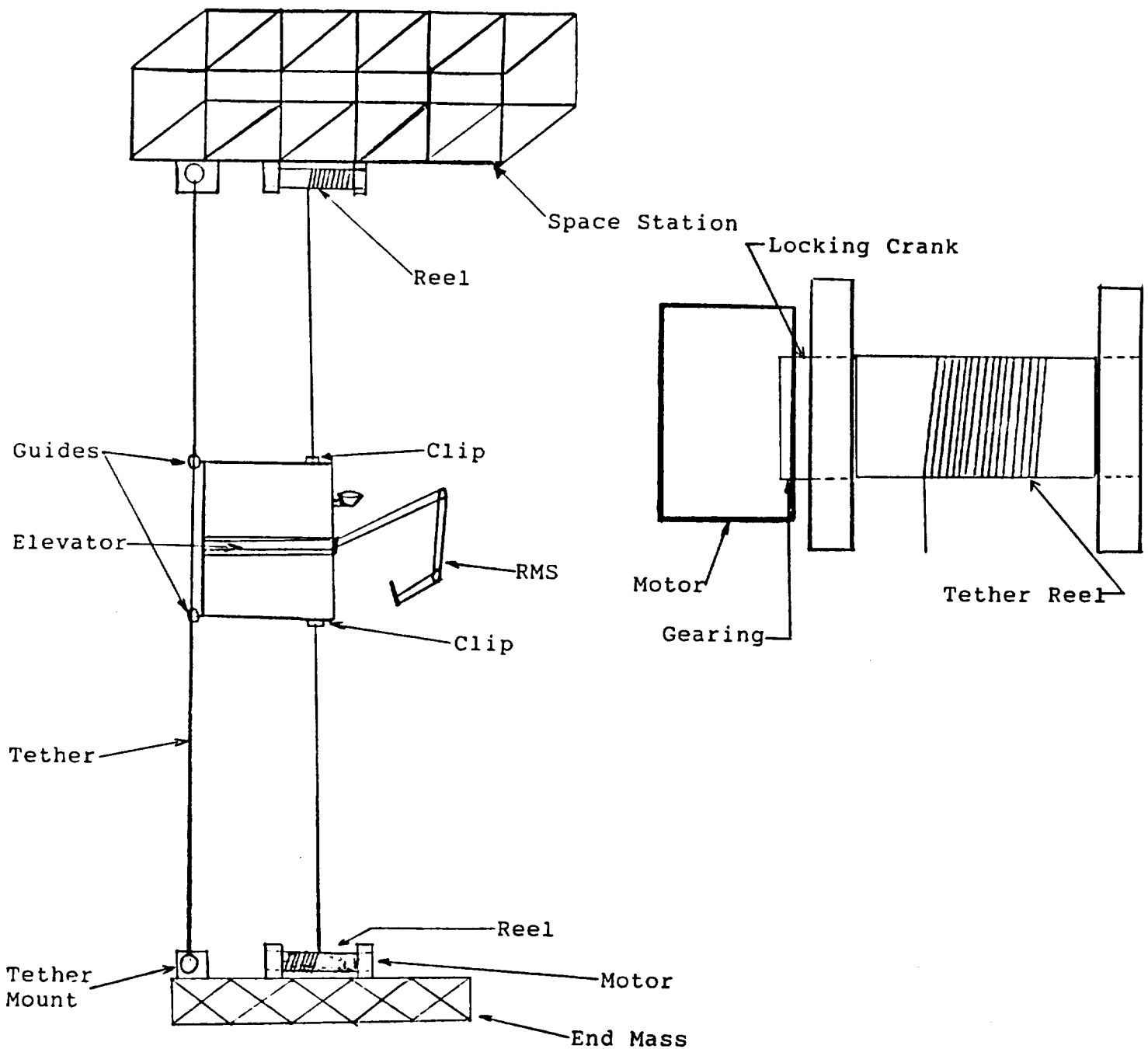


Figure 3.10

released. The elevator can now be transported via the manipulator arm along the Space Station or end mass structure.

There are several advantages to this system. It would not require elevator volume. Maintenance and repair are simplified. Also, the system is highly redundant. If either of the two powered tethers were severed, the elevator would remain under control and continue on its intended mission or return to its starting point. If the permanent tether were severed, operation of the elevator would continue as normal.

Many disadvantages of the system are known at this time. First, the problem of tether tangle could seriously hamper the operational capability of the system. Another problem with the system is that if tether sever occurred to the bottom tether while the elevator traveled from the end mass to the Space Station, the elevator would accelerate uncontrollably due to the centrifugal force until impact with the Space Station occurred. This problem would work in reverse for the return trip.

#### 31.3.3 Wrap Around Spool

The final design consideration of the spool type is that of the wrap around spool. This design, shown in Figure 3.11, can be used with any elevator configuration. The design consists of two spools that are mounted directly on the top and bottom of the plane or surface of the elevator that faces the tether. An extended tether is wrapped around the spool either one or two times depending on the load of the elevator and amount of frictional contact between the tether and spool. The friction force between the tether and spool allows the tether to be pulled around the spool and released out the other side.

This design involves two spools that are wrapped in a high friction material such as rubber. The spools are rotated by a small D.C. motor that can be internal to the spool or placed along side it with a connecting shaft. The motor will have a gear package to insure the proper rotational speed is transferred. A locking crank will be employed to insure no backlash or backslip will be experienced. Guides will be incorporated to insure entanglement does not occur.

The main disadvantage of this system is the method of attaching the spool to the tether. This would require a very complex movement of the manipulator arm or the use of an EVA. Due to this problem, it is suggested that the drive mechanism remain attached to the tether at all times. To unload materials at the Space Station or end mass, only the elevator component would be removed. Another disadvantage of this

# WRAP AROUND SPOOL DRIVE MECHANISM

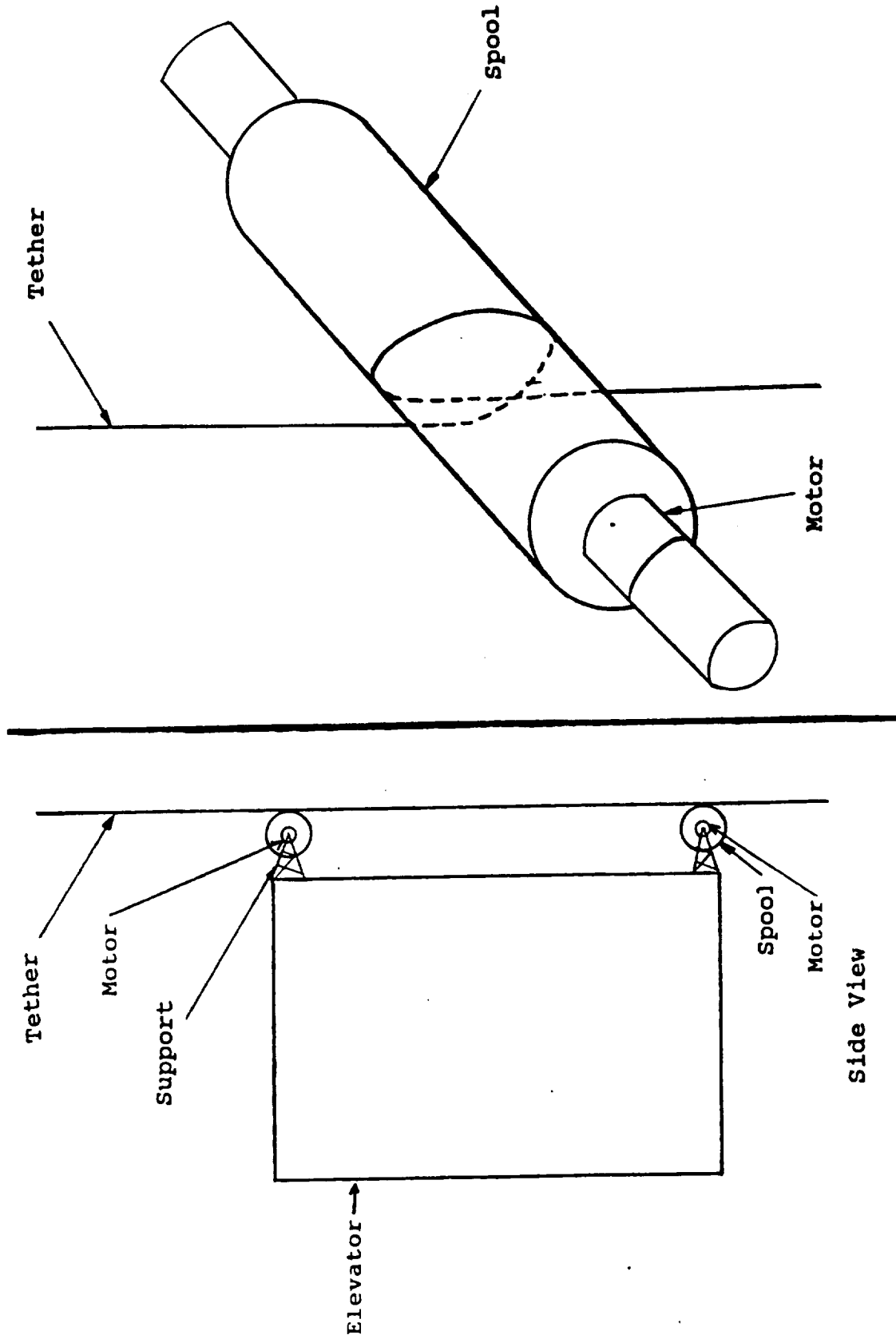


Figure 3.11

system is that the possibility of the tether becoming tangled while travelling around the spool is very high.

#### 31.4 Robotic

The robotic drive mechanism category of design considerations investigates the possibility of dragging the tether utilizing two pincers. The robotic drive mechanism consists of two, long motor driven screws upon which a motor driven pincer can translate.

The robotic drive mechanism is shown in Figure 3.12. The two long screws have recirculating ball bearings and are capable of driving the pincers in both directions. One pincer grasps the tether. The rotating screw translates the pincer the entire length of the screw dragging the tether with it. During this operation, the second pincer is in an open position and returns to its original position. This second pincer would then grasp the tether and drag it the length of the screw while the first pincer returned to its original position. This procedure would be repeated thus propelling the elevator along the tether.

The opening and closing of the pincer jaws is controlled by a small torque motor.[37] The grasping of the tether utilizes electromagnets mounted on the ends of the pincers which produce an adequate pressure force for tether dragging. The force produced is measured by a piezo-electric transducer. The power of the electromagnets can be increased or decreased by a differential transformer to control the pressure on the tether.[37] In the event of slipping, the current to the electromagnet could be increased, thus increasing the pressure of the pincers on the tether.

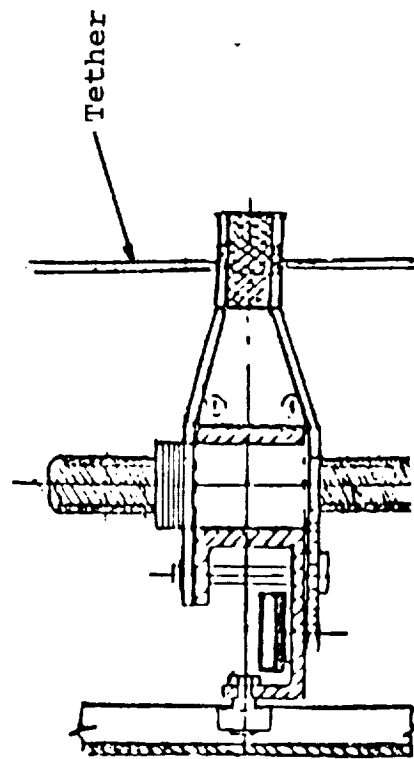
The main disadvantage of the robotic drive mechanism is that its maximum velocity can not exceed 0.5 meters per second and its maximum dragging force is 150 N.[37] Although this particular robotic drive mechanism does not meet all design requirements, variations of this design may be applicable.

#### 31.5 Electromagnetic

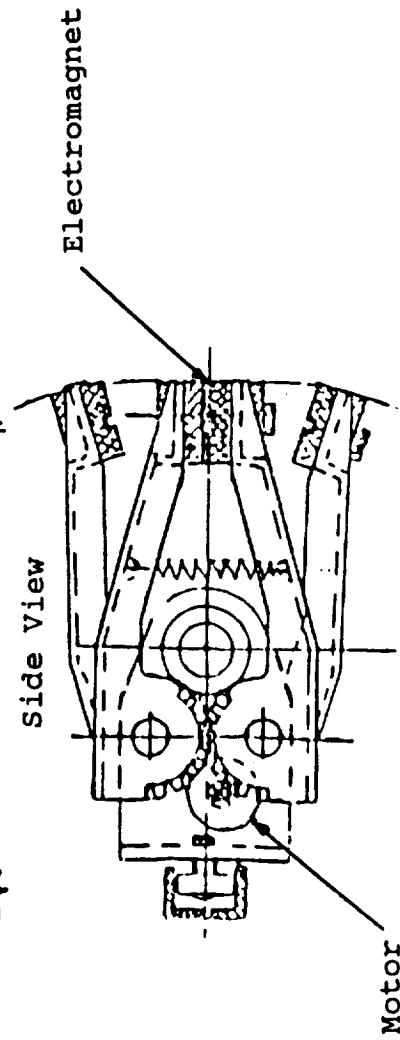
The use of electromagnets have been considered as a possible drive mechanism. This propulsion concept utilizes the force of a core immersed in a magnetic field created by a coil. This system is shown in Figure 3.13. This magnetic field can be progressively turned on and off to drag or propel this core along. For the drive mechanism application, many of these coils would have to be used. These coils would have to be positioned out of phase in reference to the core

# ROBOTIC DRIVE MECHANISM

Pincers



Side View



Top View  
Top View

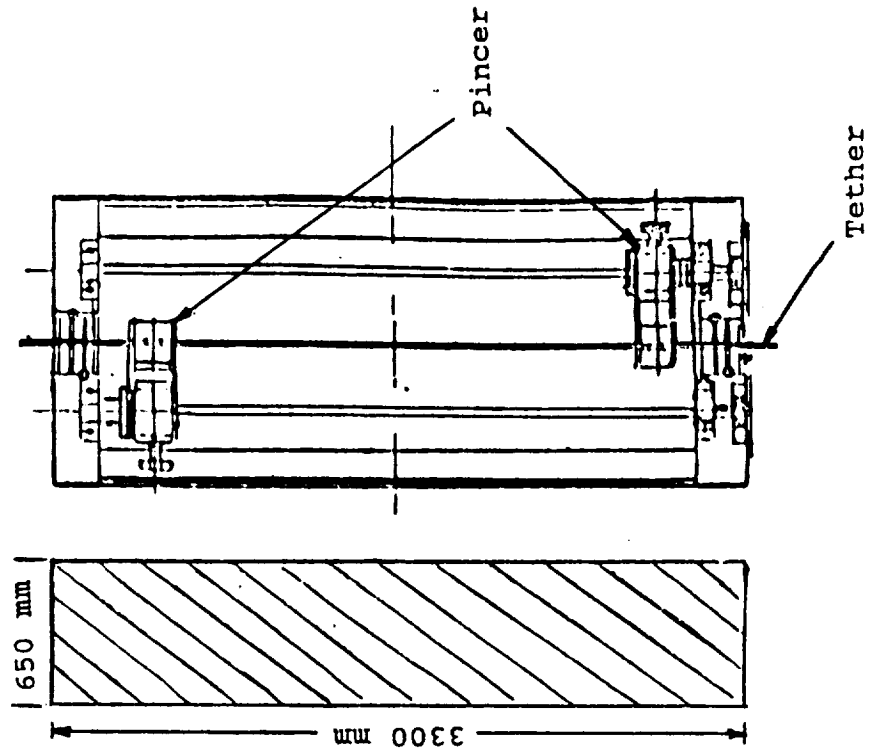
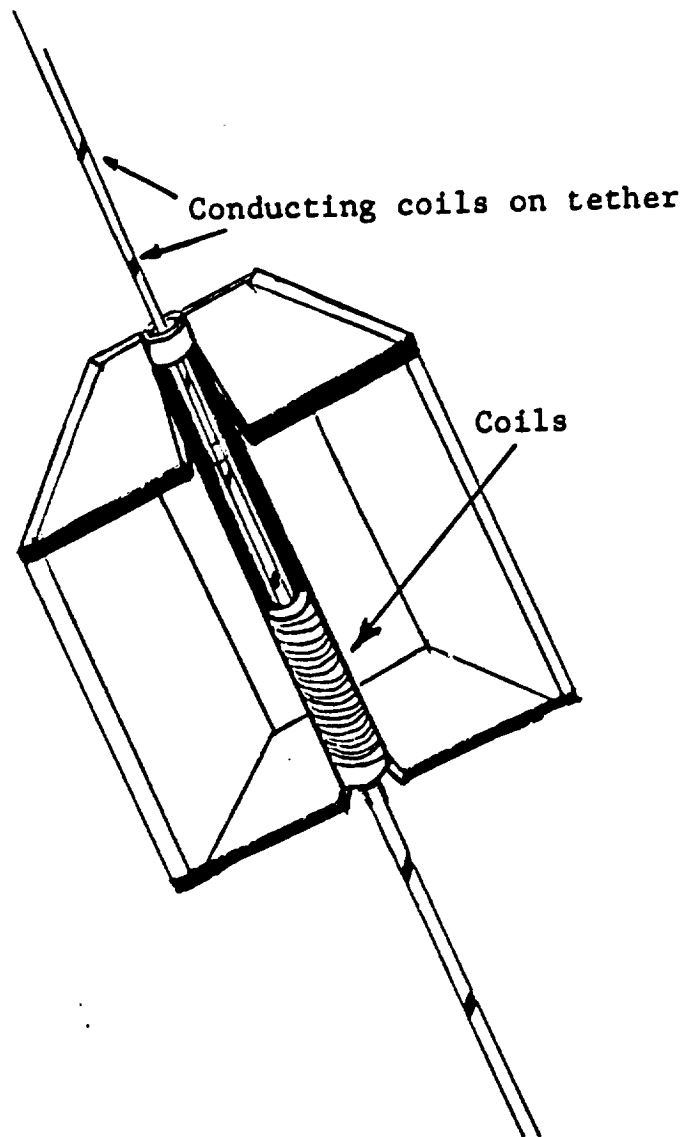


Figure 3.12

## ***ELECTROMAGNETIC DRIVE MECHANISM***



**Figure 3.13**

positions.[37] To realize a continuous movement of the drive mechanism in both directions a switching procedure is used. The switching procedure requires a precision on and off sequence of the coils. One aspect of this drive mechanism is that the build up of heat in the coils would have to be dissipated. The braking of the drive mechanism would be simply a matter of turning off the proper coils.

The possibility of dragging a 5000 kg mass along a tether of diameter 17 mm exchanging a maximum force of 150 N with a speed of a 5 m/s has been investigated. A total electrical power of 2860 W with a current of 5.34 amps in the coils would be required.[37]

The main advantage of an electromagnetic drive mechanism would be the simple incorporated braking method. The main disadvantage would be the large amount of power required for operation.

### 31.6 GAS SYSTEMS

The final category of design considerations that will be investigated is that of gas systems. Refer to Figure 3.14. There are two types of gas systems that will be explained. They include:

1. Cold Gas System.
2. Hypergolic Gas System.

#### 31.6.1 Cold Gas System

The cold gas system subcategory uses a series of small gas engines to propel and stabilize the elevator. Refer to Figure 3.14. The use of cold gas propellant in the environment of space requires that both a fuel and oxidizer be used in the combustion process. The fuel used in the system will be liquid hydrogen (LH<sub>2</sub>) and the oxydizer will be liquid oxygen (LOX). Both the fuel and oxydizer are considered cyrogenic because they must be stored at temperatures below 50 K.[39] The fuel and oxidizer tanks would have to be stored on the elevator structure.

The main disadvantage of the cold gas system is that of the storage of the cryogenic fuels. Storage of the fuels for long periods of time at very low temperatures in a space environment would be very difficult. Another disadvantage would be the volume that the system would occupy on the elevator. The cold gas system would greatly reduce the cargo capacity of the elevator. The final disadvantage would be



## *COLD GAS DRIVE MECHANISM*

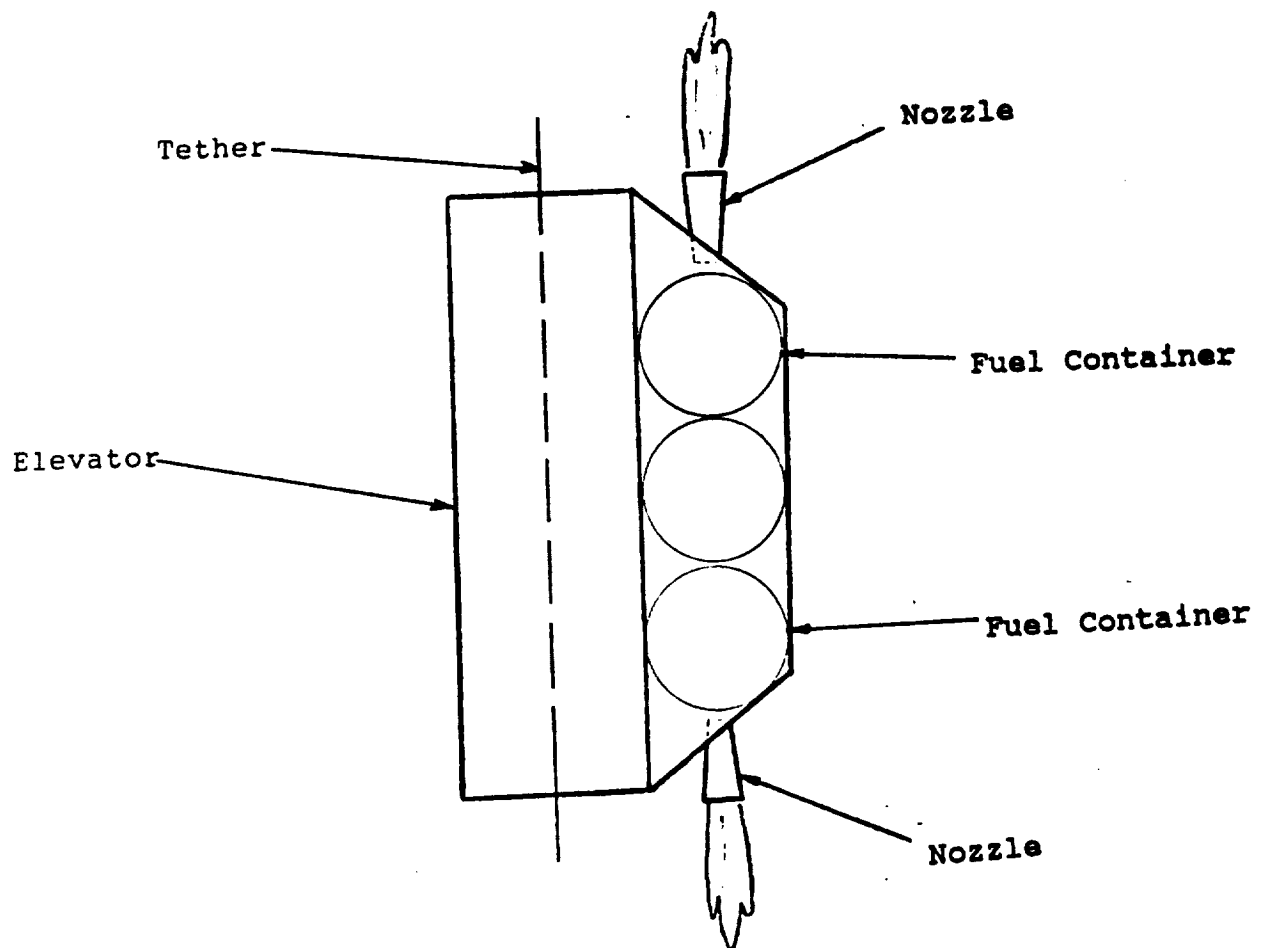


Figure 3.14

that control of the elevator would require complex motion control procedures.

### 31.6.2 Hypergolic Gas Systems

The second subcategory of the gas systems is that of hypergolic gas systems. A hypergolic gas system would use a series of small engines to propel and stabilize the elevator during tether traversing operations. As before, the use of hypergolic propellants requires both an oxidizer and fuel. The fuel used in this system would be hydrazine and the oxidizer would be nitrogen tetroxide. The unique characteristic of this fuel-oxidizer combination is that combustion takes place without an initial ignition source. Provisions must be made on the elevator to house the engines and fuel storage tanks.

There are several disadvantages with the hypergolic gas system. First, the overall size of the engines and associated fuel tanks will greatly reduce the amount of available cargo space on the elevator. Next, the control of the elevator will require the use of complex motion control procedures. The only advantage of the hypergolic gas system over the cold gas system is that the storage of the fuel and oxidizer is much easier.

## Chapter 32. HOOK / UNHOOK SYSTEM

The hook / unhook system will be used in conjunction with the tethered elevator system and specifically the drive mechanism. The hook / unhook system will provide a simple and efficient method of attaching and detaching the elevator and drive mechanism from an extended tether. The hook / unhook systems that have been considered must meet the design requirements previously mentioned. The design considerations that have been investigated include:

1. Folder Guide
2. Cylinder Guide
3. Spiral Guide
4. Spool Guide
5. Funnel Guide

### 32.1 Folder Guide

The folder guide is designed to first guide the tether into a section of pipe that has had one quadrant cut out of its side wall. Once the tether has been directed into the pipe, the guide walls will close to lock the tether in place. See Figure 3.15. The folder guide pipe must be made of a

*FOLDER HOOK /  
UNHOOK GUIDE*

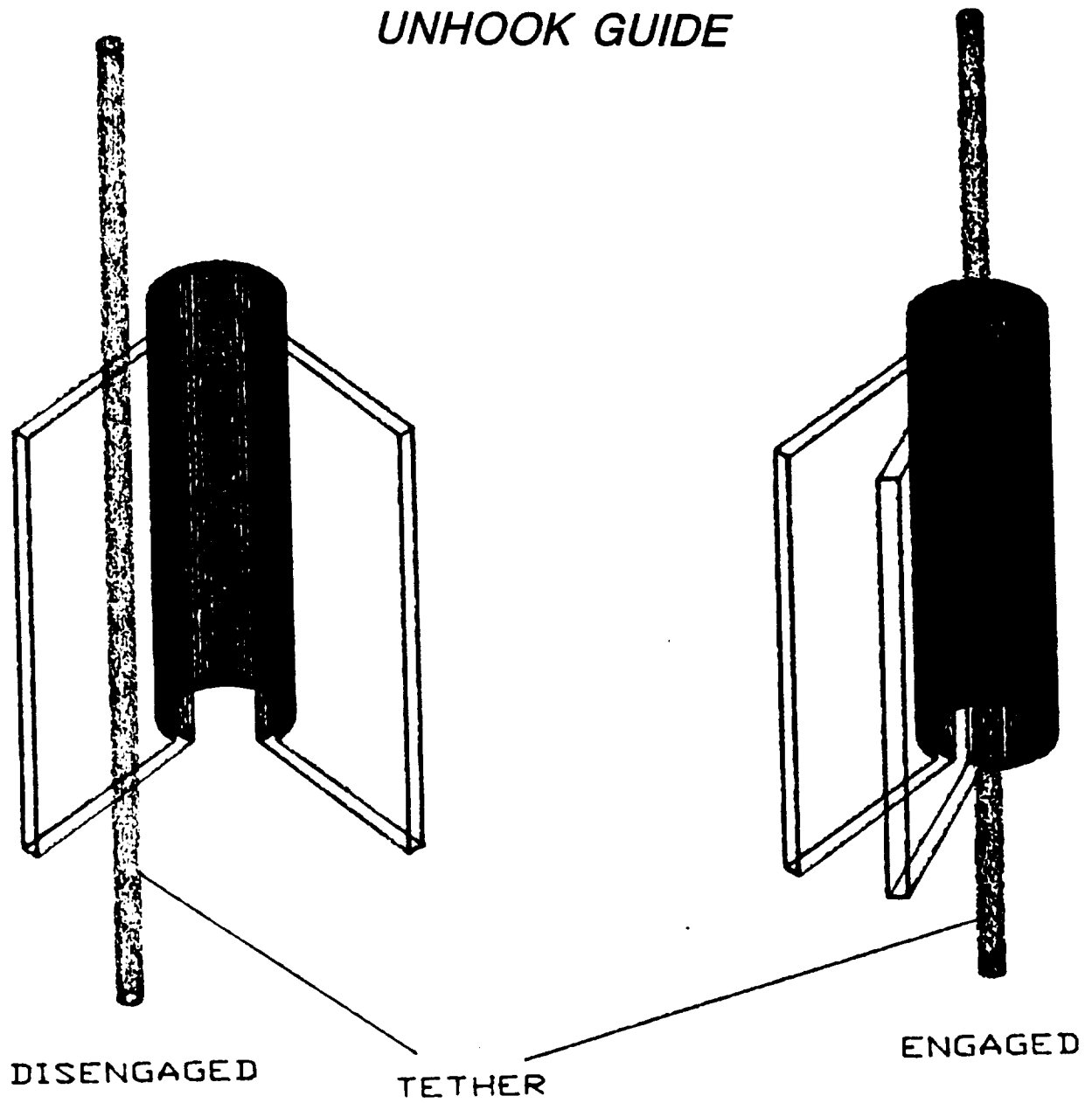


Figure 3.15

flexible material which can permit the folding of the guide walls. Actuators or small electric motors not shown in the figure are used to fold the guide walls of the system. To remove the tether from the folder guide system the guide walls are simply unfolded allowing the RMS to pull the elevator and drive mechanism from the guide pipe.

The main advantage of the folder guide is its ability to guide the tether through the use of extended guide walls. One of the disadvantages is the possibility of excessive wear of the material used in the flexible pipe as the guide folds and unfolds to hook and unhook the elevator from the tether.

### 32.2 Cylinder Guide

The cylinder guide is composed of two interlocking cylinders which hold the tether in place when engaged. See Figure 3.16. Cylinder guides located on both ends of the elevator will engage simultaneously, locking the tether in line with the friction belt or friction wheels used in the drive mechanism. The latch used to close the guide would be driven by a worm gear mechanism not shown in the figure. To unhook the system, the latch will slide open allowing the tether to be removed.

Advantages of the cylinder guide include its simple design and compact size. The main disadvantage of the cylinder guide is the difficulty in maneuvering the tether into the relatively small opening in the cylinder.

### 32.3 Spiral

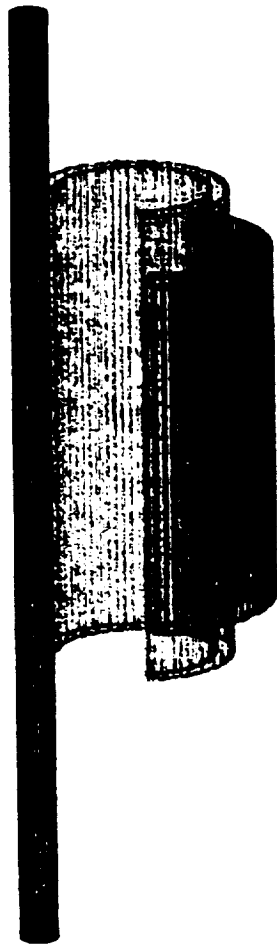
The spiral guide is simply a helix that spins around the tether until the tether is positioned at the center of the helix. See Figure 3.17. For unhooking operations, a mechanism which is not shown in the figure flips the tether around the last wrung of the spiral and the winding motion of the spiral is reversed.

The main advantage of the spiral guide is its compact size. A disadvantage of the spiral guide is the complex motion control that will be required for the proper operation of the system. If the mechanism were to malfunction, redundancy is not built into the system allowing a way to free the tether.

### 32.4 Spool Guides

Spool guides were also evaluated in the design considerations. The spool guide is simply two spools, or

*CYLINDER HOOK/  
UNHOOK GUIDE*



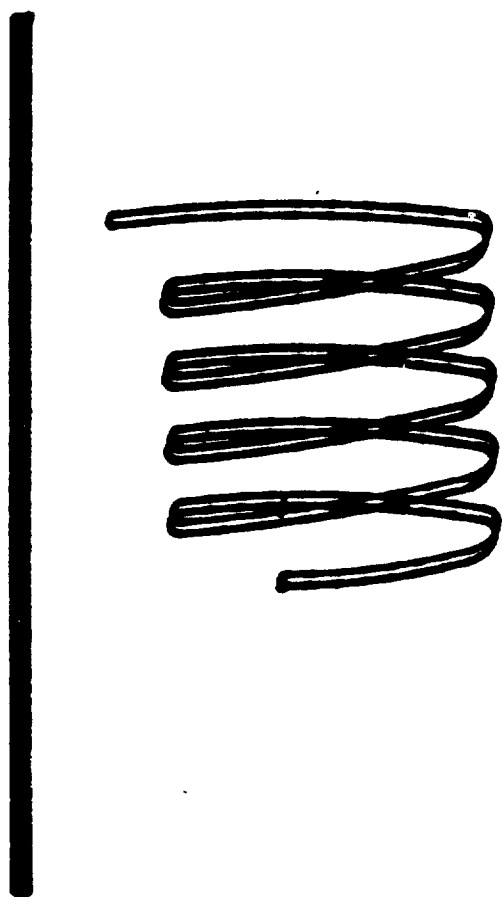
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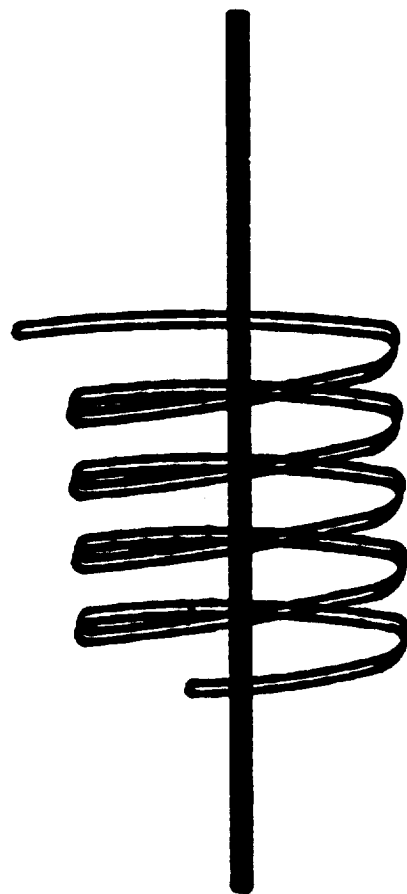
ENGAGED

Figure 3.16

*SPIRAL HOOK/  
UNHOOK GUIDE*



DISENGAGED



ENGAGED

Figure 3.17

rollers which are aligned perpendicularly when disengaged and parallel when engaged. See Figure 3.18. The tether is positioned between the two spools when the hook / unhook system is engaged. To disengage the tether one of the spools is rotated, creating a large opening. This large opening makes hooking and unhooking operations much easier. One spool guide system would be located at either end of the elevator.

The advantage of the spool guide system is the relative simplicity and ease of the operation. The components of the spool guide are simply two spools and a mechanism to lock the spools in place. The spools can easily be adjusted for various tether diameters by varying the distance between the spool surfaces.

### 32.5 Funnel Guides

As shown in Figure 3.19, the fifth design consideration for the hook / unhook system is the funnel guide. The funnel guide is basically a modified cylinder guide. The main modification of the system has been the installation of the rigid guide walls as opposed to the moveable types used in the cylinder guide. The semi-cylindrical pipe configuration allows the tether to be easily latched inside the pipe cylinder, while the guide walls assist in guiding the tether to this location.

The main advantage of the funnel is its ease of operation. The tether can easily be guided into the funnel guide for hooking. The tether can easily be removed from the funnel guide by simply moving the semi-cylindrical latch allowing the tether to move freely.

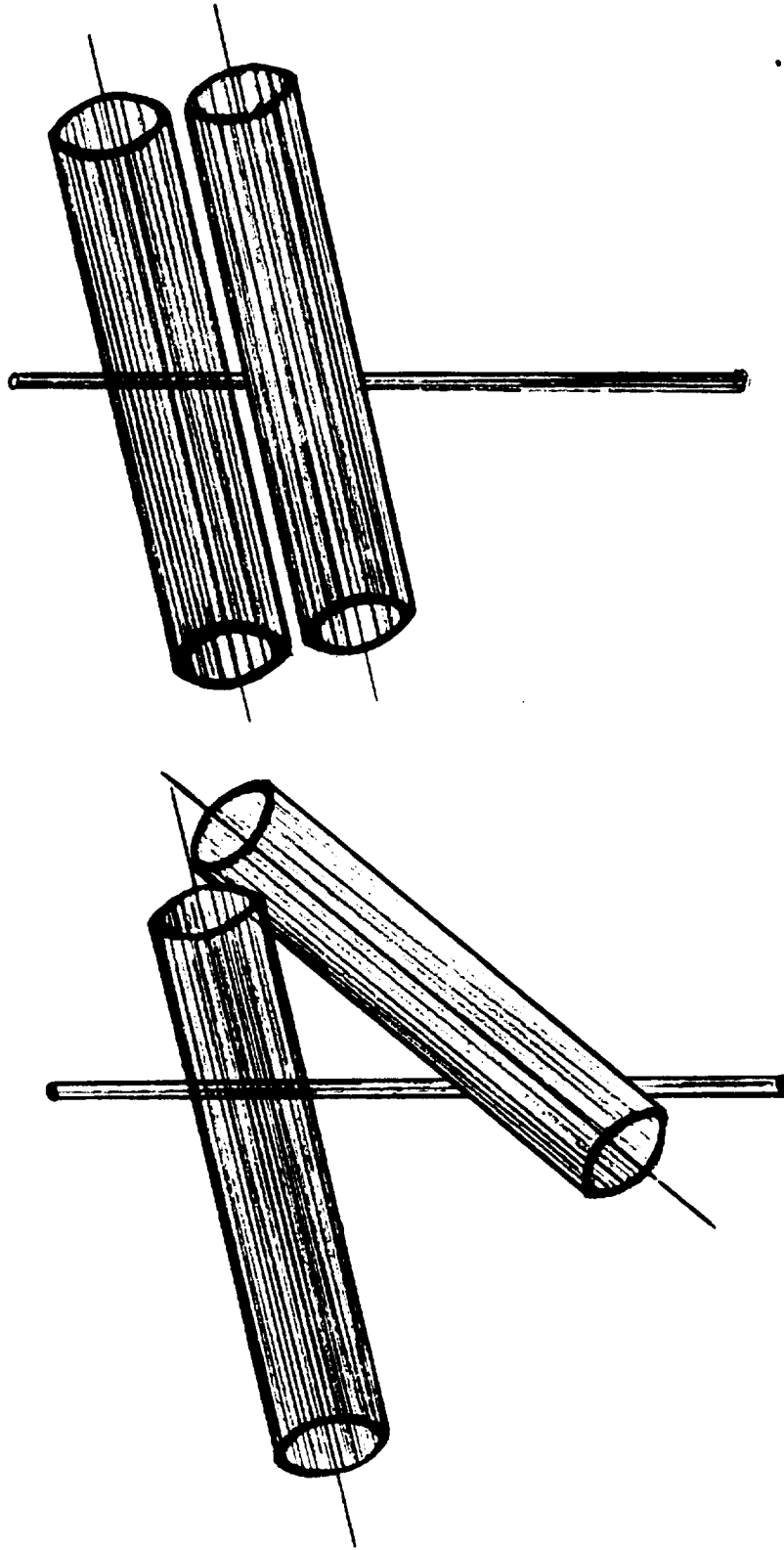
## Chapter 33. CAPTURE AND DRIVE MECHANISM PHASE I - OPTIMAL SOLUTION

In this chapter the optimal solutions for the drive mechanism and hook / unhook procedure will be presented.

### 33.1 Drive Mechanism

According to the Solution Matrices 3.1 - 3.4, the friction belt category of design considerations proved to be the most capable of meeting the drive mechanism's design requirements. All three friction belts, the tri-wheel, the bi-wheel, and the quad-wheel, achieved total weighted values ranking higher than the rest of the other design considerations.

*SPOOL HOOK/  
UNHOOK GUIDE*



ENGAGED

DISENGAGED

Figure 3.18



*FUNNEL HOOK/  
UNHOOK GUIDE*

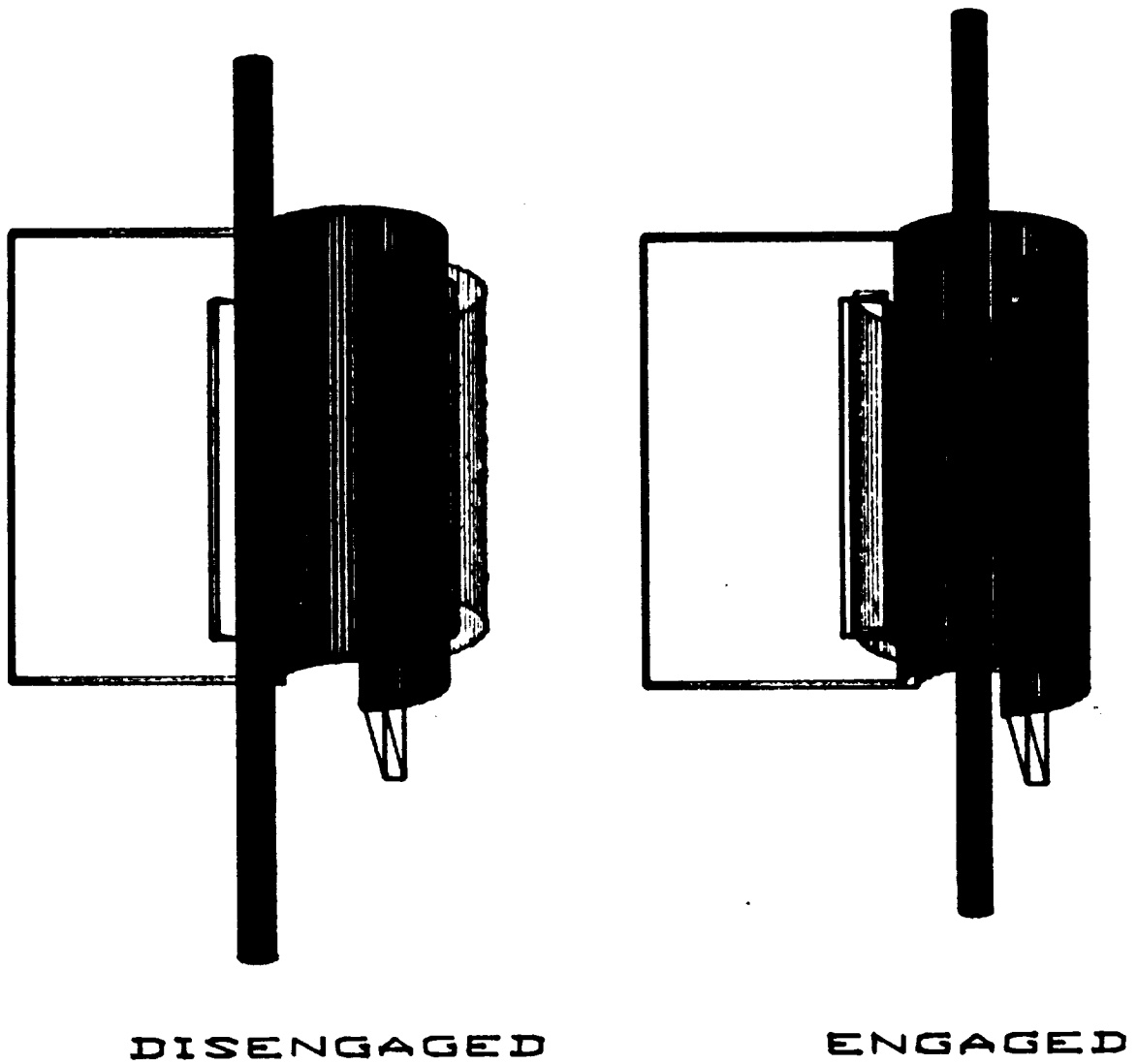


Figure 3.19

Of the friction belt drive mechanisms, the bi-wheel friction belt was chosen as the "best" or optimal solution. The bi-wheel utilizes the same basic operating theory as the tri-wheel friction belt but with many additions and modifications. Refer to Figures 3.20 and 3.21 for a complete drawing of the proposed bi-wheel friction belt and its components.

The bi-wheel friction belt will utilize two "adjustable-speed motors" to drive its two friction belts. In this type of motor, the speed can be varied gradually over a considerable range, and when adjusted remains practically unaffected by its load. The type of motor recommended is a reversible, direct-current shunt-wound motor with field resistance control designed for a considerable range of speed adjustments.[40] Refer to Figure 3.22 for a drawing of the motor.

The bi-wheel will utilize four pulley wheels. Two of which are driven by the motors and the other two are simply idlers. All four of the pulley wheels will be of the toothed type design enabling them to drive the synchronously toothed friction belt with minimal slip. Refer to Figure 3.23 for detailed drawings of the toothed pulleys.

The bi-wheel will utilize a synchronous friction belt to overcome any creep characteristics. A synchronous belt is just a toothed belt with an associated toothed pulley. The belt will be made with Neoprene teeth covered by nylon and internally reinforced by rayon cord. Refer to Figure 3.24 for detailed drawings of the toothed friction belt.

To maintain the toothed friction belt's proper pressure force against the tether (without slipping) a linear actuator will be used. A linear actuator provides straight-line reciprocating motion. Mounted on the linear actuator will be a pressure block with rollers. The pressure blocks are responsible for maintaining proper contact between the belt and tether. One pressure block is fixed and the other is mounted on the actuator, capable of reciprocating linear motion. Refer to Figures 3.25 and 3.26 for detailed drawings of the linear actuator and pressure blocks.

### 33.2 Hook / Unhook

According to the Solution Matrix 3.5, the funnel guide was deemed the most feasible for the hook / unhook procedure.

The cylindrical pipe configuration, shown in Figure 3.27, allows the tether to be easily placed inside the pipe cylinder, while the guide walls assist in guiding the tether to its location in the drive mechanism.

# BI-WHEEL FRICTION BELT (OPTIMAL SUBSYSTEM)

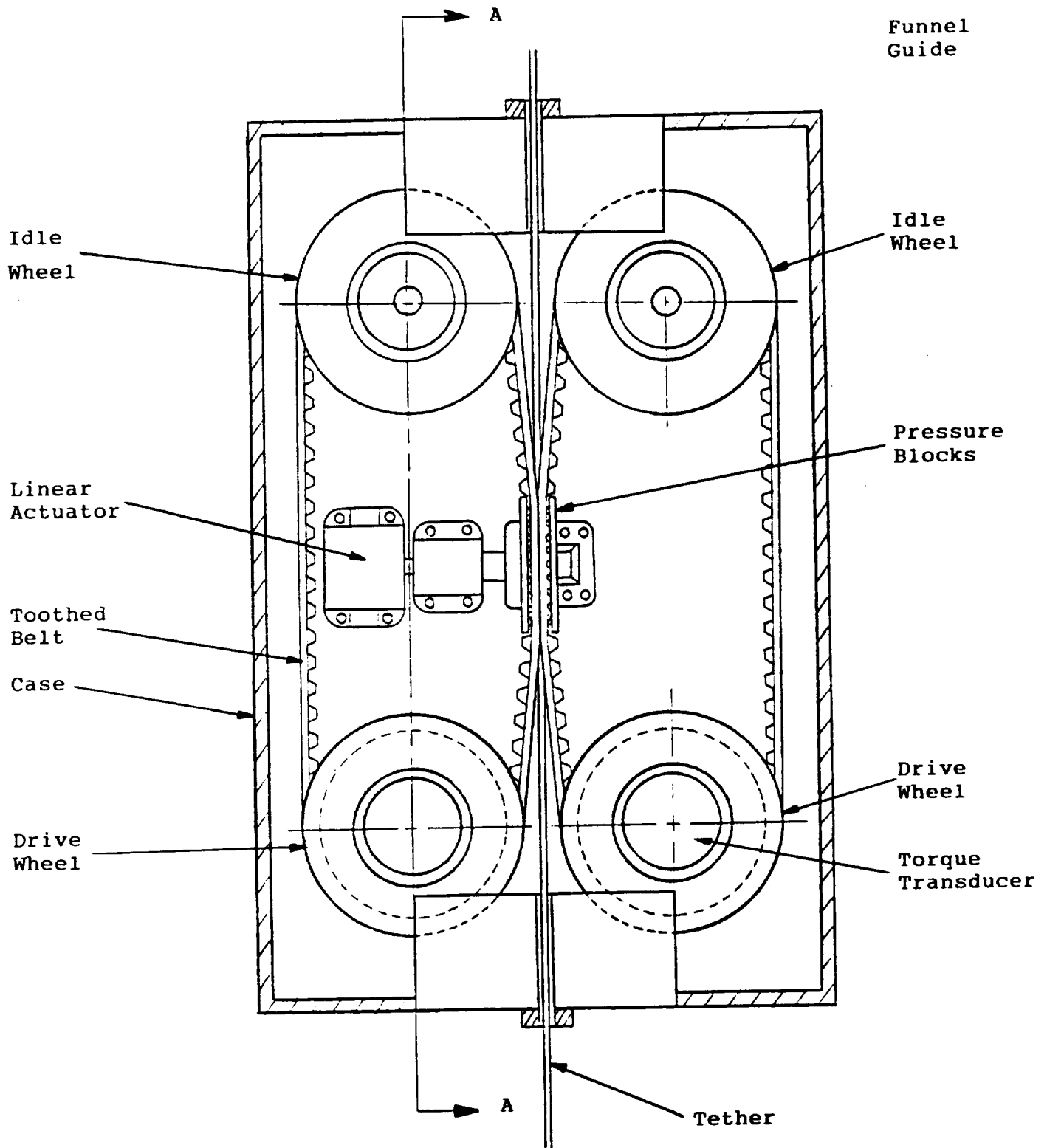


Figure 3.20

## BI-WHEEL FRICTION BELT (COMPONENTS)

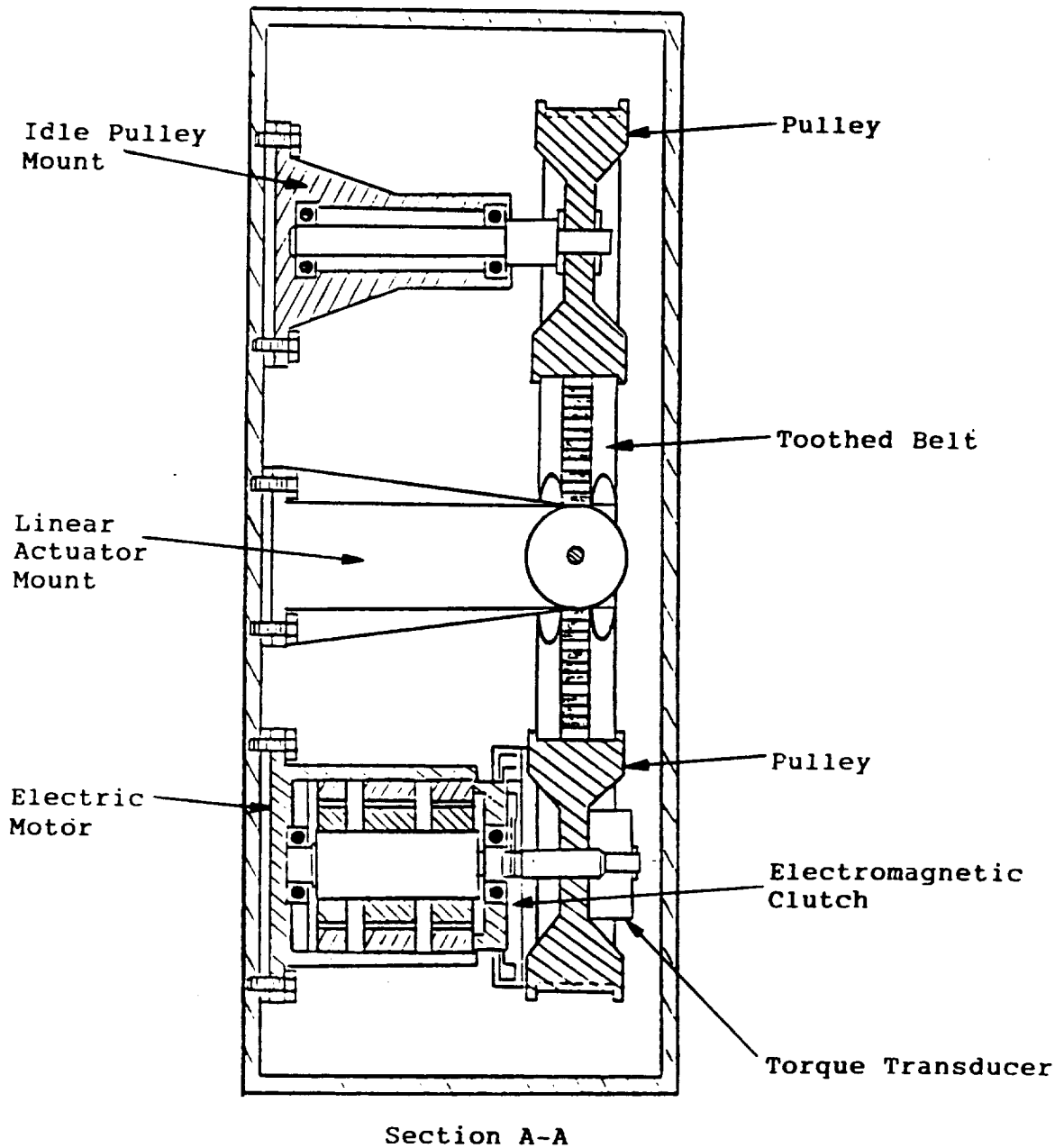


Figure 3.21

## FRICTION BELT MOTOR

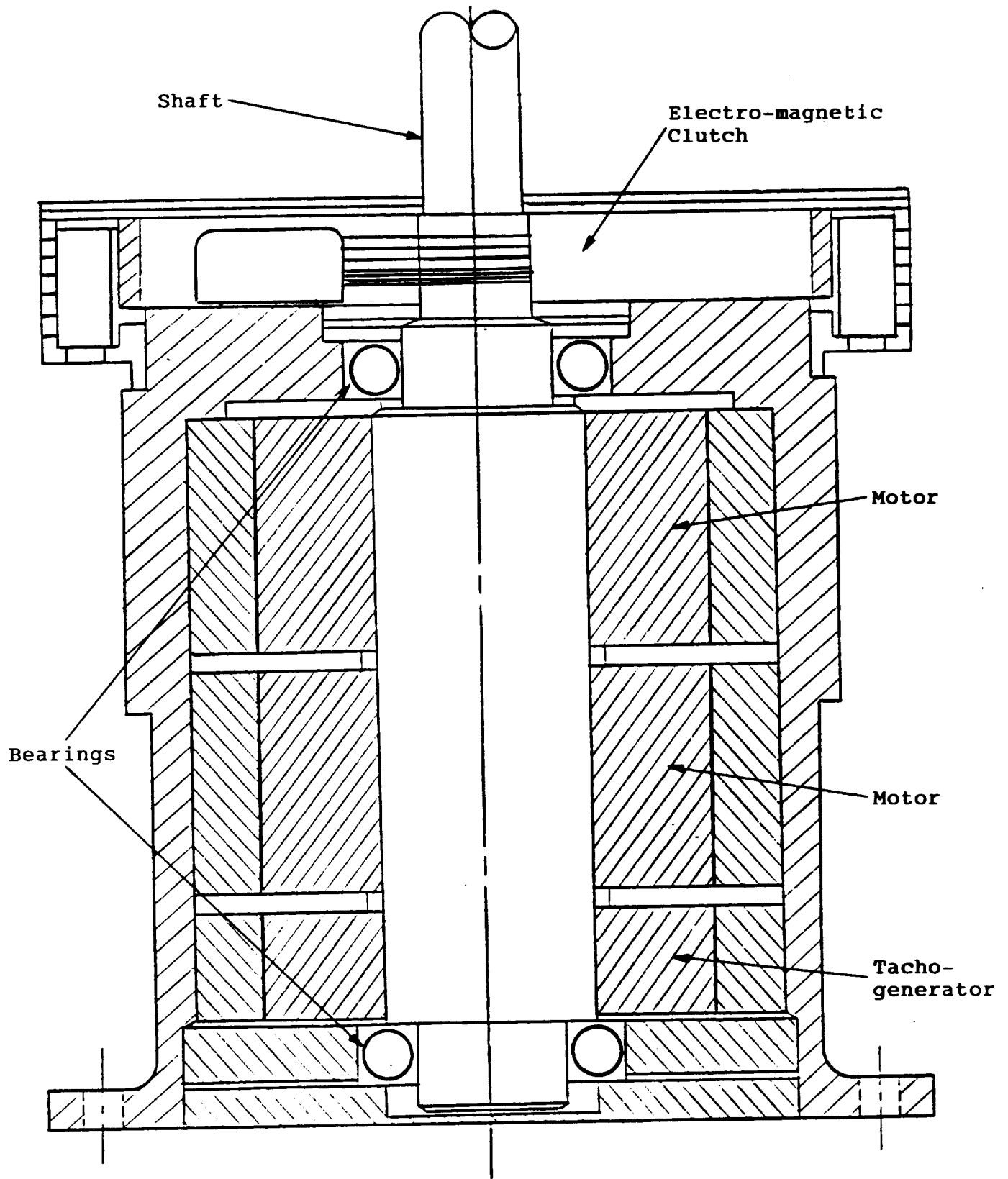
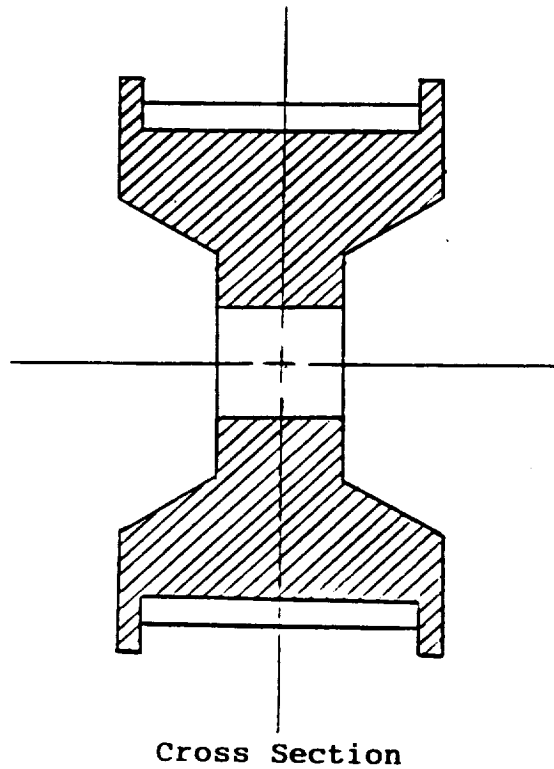
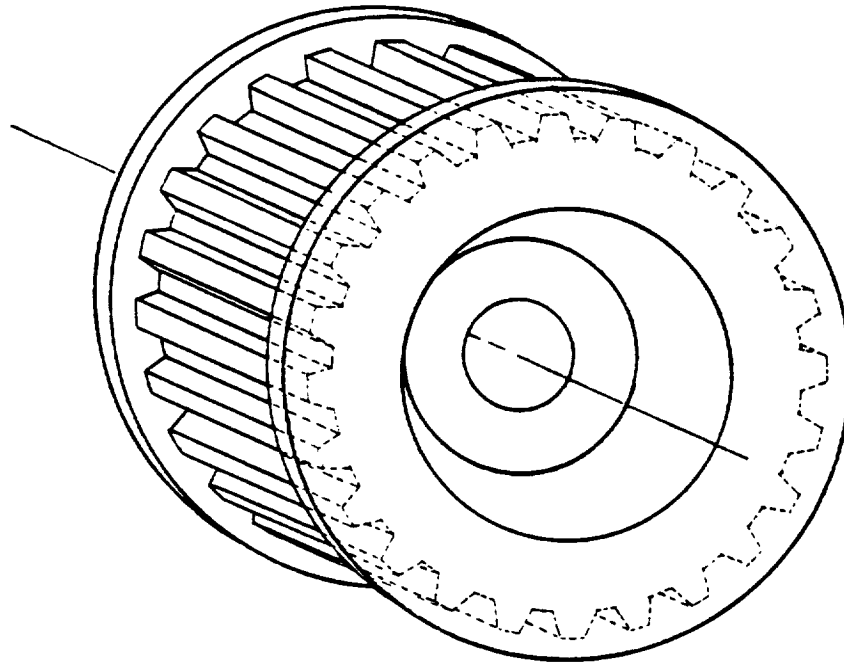


Figure 3.22

## ***FRICTION BELT PULLEYS***



**Figure 3.23**

## *FRICTION BELT / PRESSURE BLOCKS*

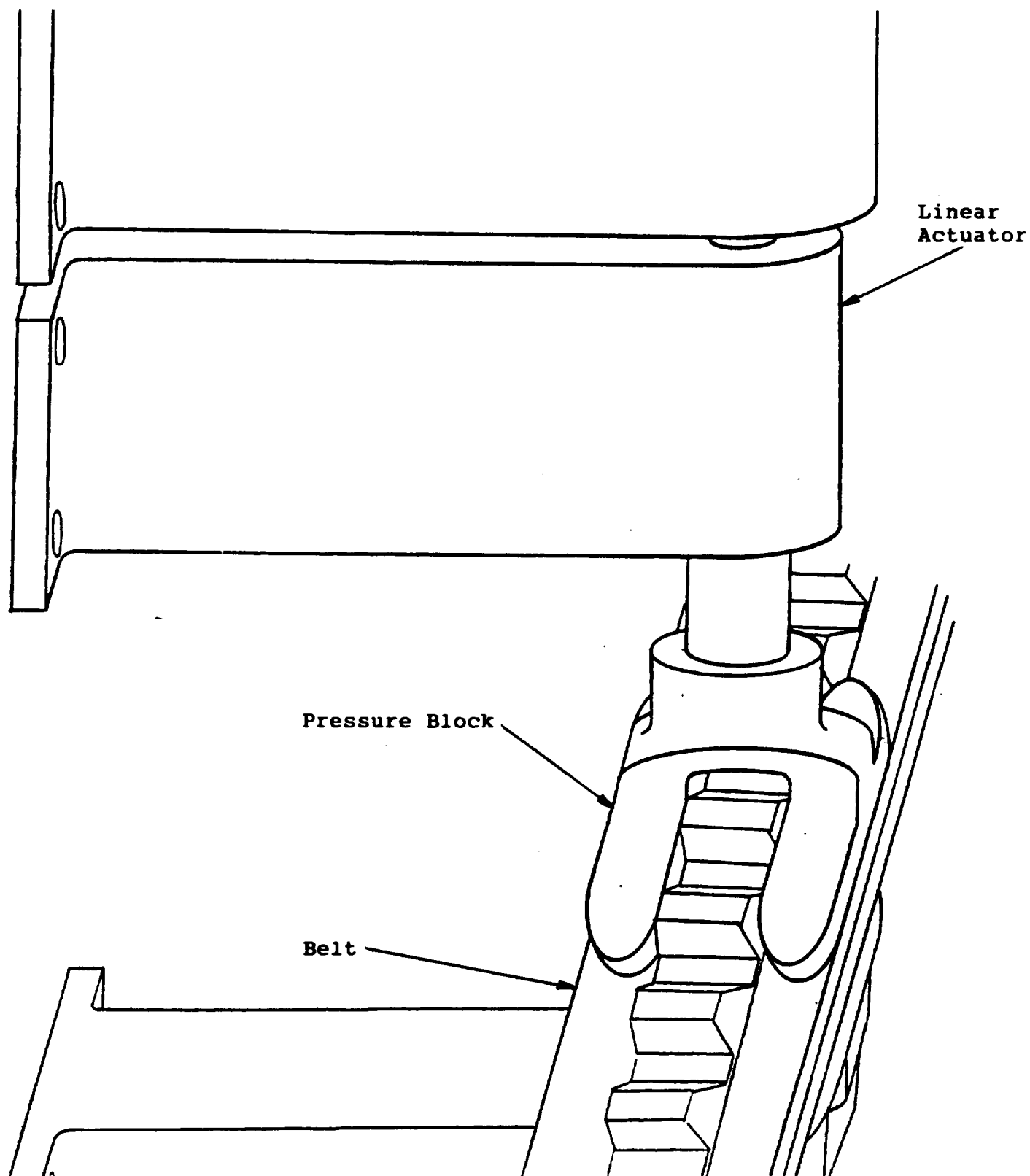


Figure 3.24

## *FRICTION BELT LINEAR ACTUATOR*

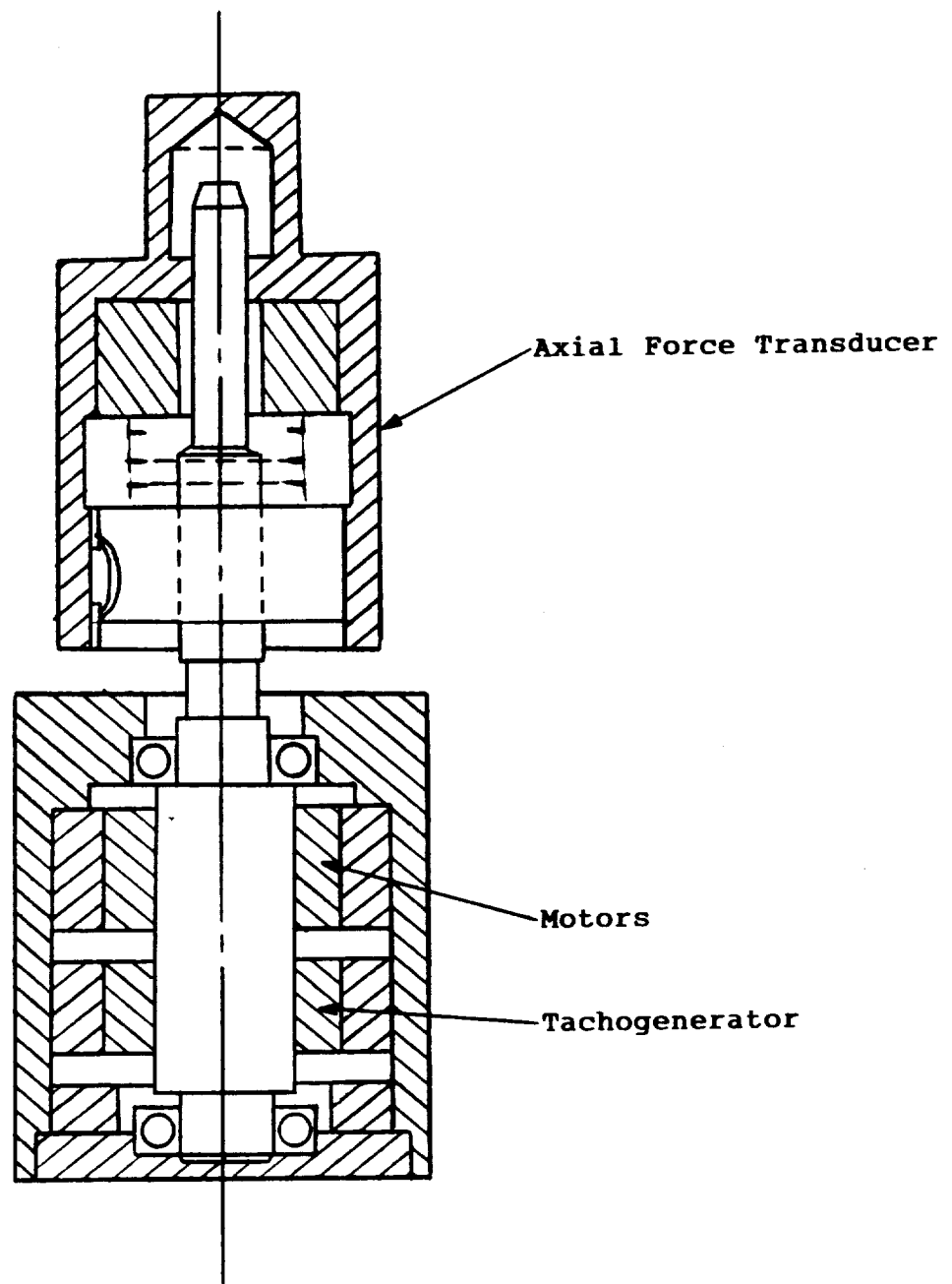


Figure 3.25



## *PRESSURE BLOCKS*

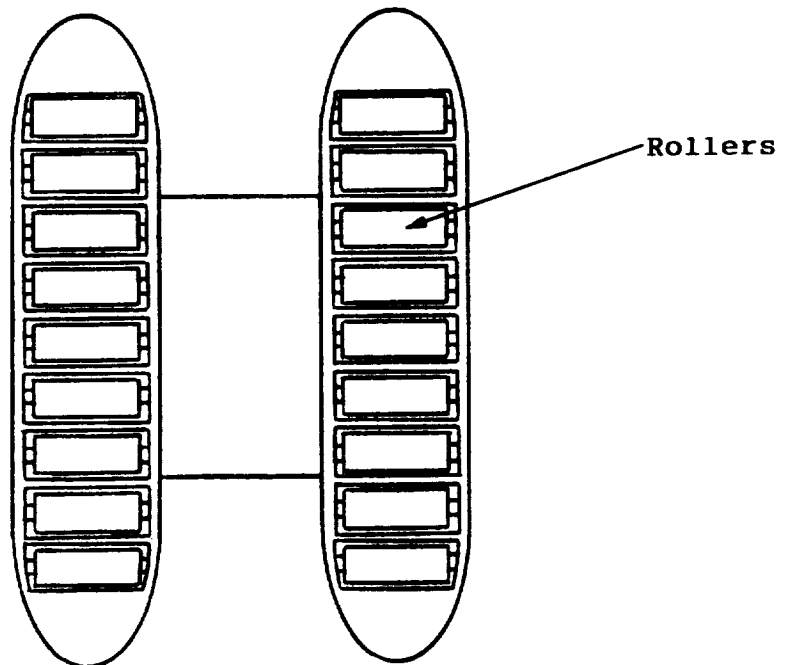
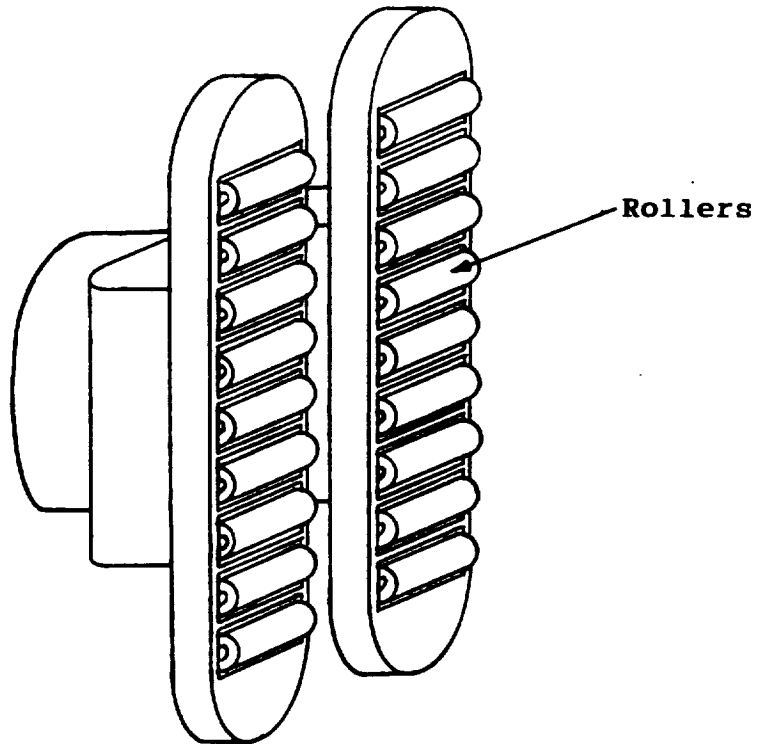


Figure 3.26

*HOO K / UNHOO K OPERATION  
(OPTIMIZED SUBSYSTEM)*

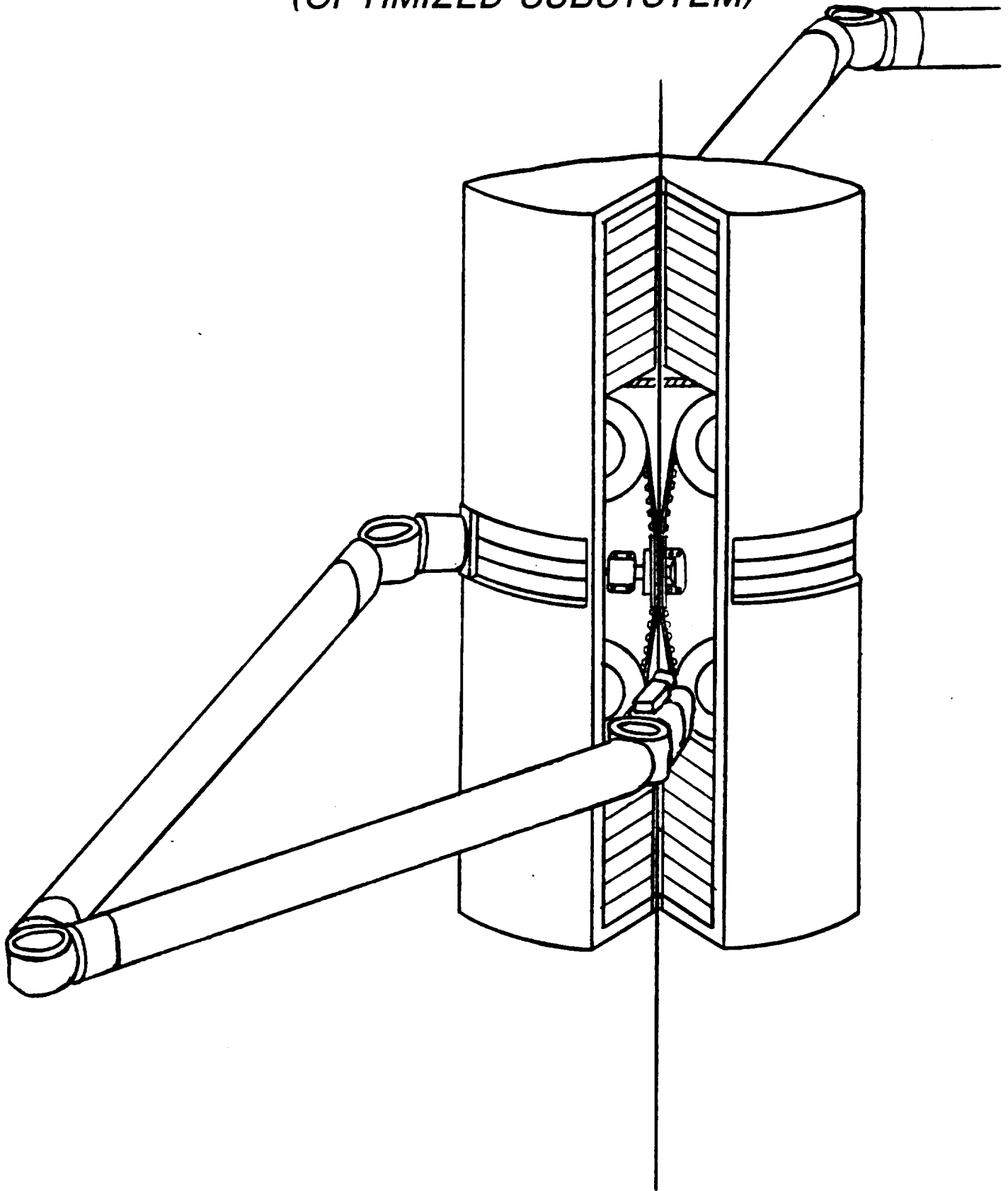


Figure 3.27

## DESIGN PHASE II. TETHERED ELEVATOR CAPTURE AND DRIVE MECHANISM

This phase of the capture and drive mechanism design involves reanalyzing the work done in Phase I with additional analysis on belt interface and materials. The following preliminary capture and drive mechanisms were studied their operation feasibility:

1. Hook / Unhook Mechanism
2. Drive Mechanism
3. Sliding Block / Friction Belt Interface
4. Braking Mechanism
5. Materials

### Chapter 34. Hook / Unhook Mechanism

The hook / unhook mechanism will allow the elevator to be easily attached to an extended tether. The designs that were considered are as follows:

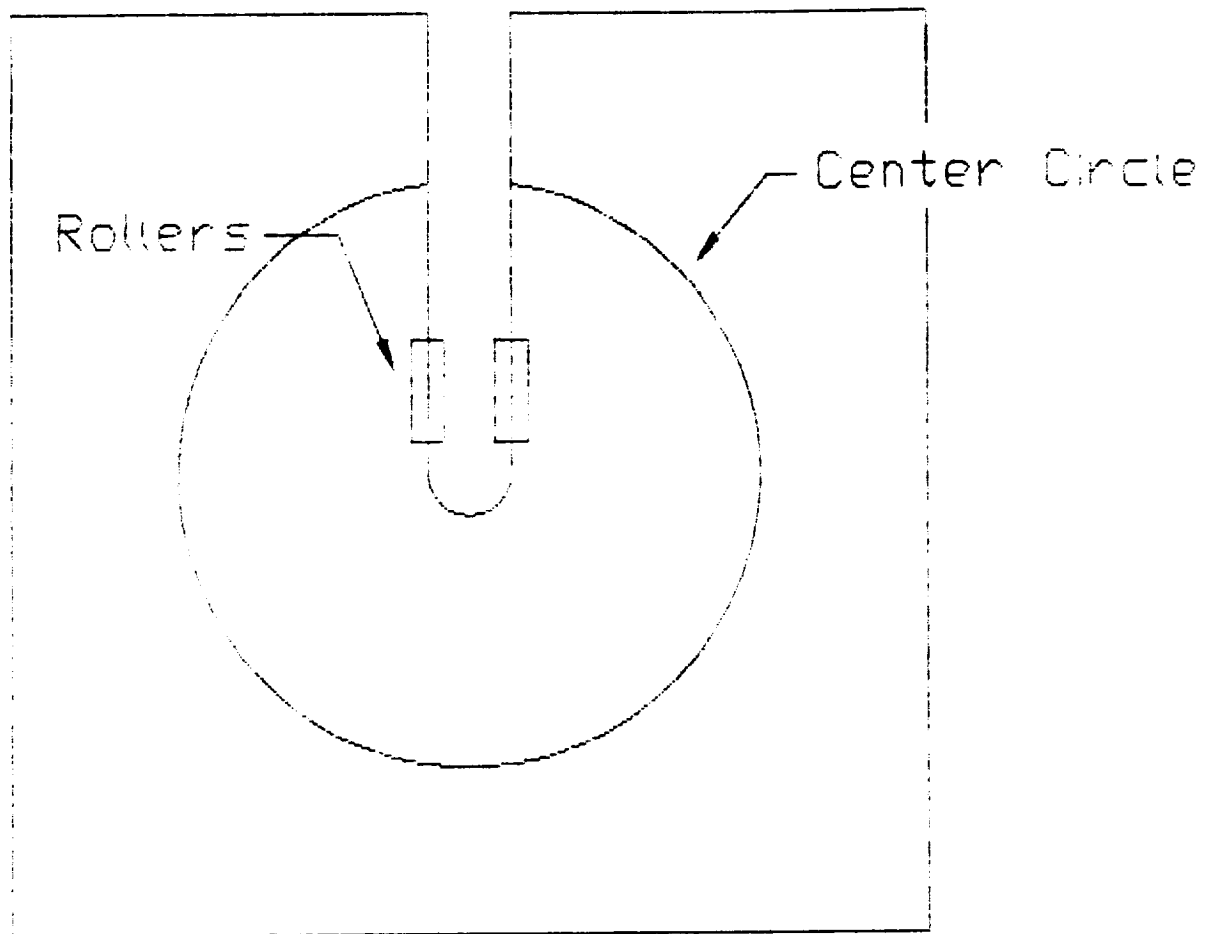
1. Rotating Disk
2. Slide Lock
3. Gate Cylinder
4. Dead Bolt
5. Locking Rings

The hook / unhook mechanism must attach the elevator to the extended tether without any damage occurring to the tether.

#### 34.1 Rotating Disk

The Rotating Disk hook / unhook mechanism is basically a circular disk that rotates about a fixed axis. This axis of rotation will be considered the center of the elevator. A diagram of the mechanism and orientation within the elevator is given in Figure 3.28. Note that the outer casing of the mechanism will be attached to the elevator. The tether is guided by the guide mechanism, mentioned earlier, to the center of the rotating disk. The center disk will rotate 90 degrees causing the tether to be captured within the mechanism. The outer casing, which is fixed to the elevator, will allow the center disk to rotate, locking the captured tether onto the elevator. The rollers attached to the left and right sides of the center disk will help prevent excess wear due to friction between the tether and the sides of the rotating disk. Rollers are omitted at the top and bottom of the center disk because the belt drive mechanism will keep the tether on a fixed horizontal plane relative to the vertical rollers.

## ROTATING DISK HOOK / UNHOOK MECHANISM



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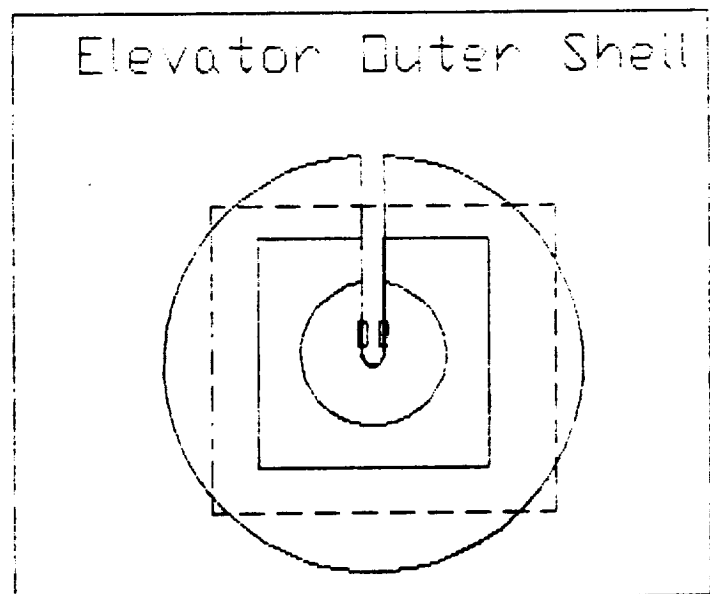


Figure 3.28

The advantage of this design is its ease of operation. The disadvantage of the design is that damage to the tether may occur if it is not located in the center of the mechanism during the rotation of the center disk.

#### 34.2 Slide Lock

The Slide Lock hook / unhook mechanism is basically the same locking device found on most common doors. The locking bolt remains in the locked position by a spring located behind the latch. As the tether is guided by the guide mechanism, the force produced by the tether onto the latch during hooking procedures will push the latch down, allow the tether to slide over the latch, and capture the tether within the mechanism. The rollers on both sides of the door latch mechanism will reduce the wear on the tether during normal elevator operation. The unhook procedure requires that a solenoid be attached behind the latch allowing it to be pulled down to release the tether. A diagram of the design is given in Figure 3.29.

The advantage of this design is its ease of operation and simplicity of design. The disadvantage of the design is the initial wear placed on the tether during the hooking operation.

#### 34.3 Gate Cylinder

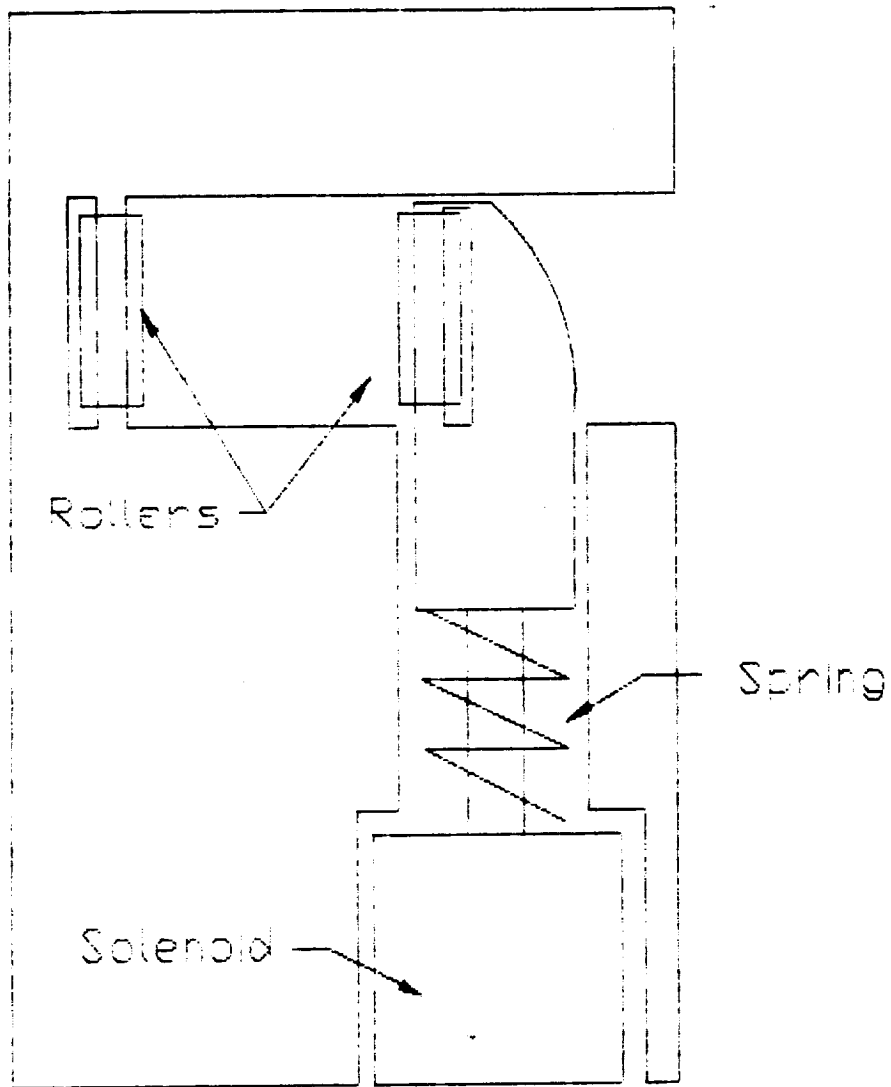
The Gate Cylinder is composed of a short cylinder with an opening. A cylinder plate, attached to the cylinder by a hinge, will open and close the cylinder for hook / unhook operation. A diagram of the device is given in Figure 3.30. The opening and closing action of the gate will be performed by a push rod which can be attached to a solenoid or rotating cam. The walls of the mechanism can be composed of a self-lubricating material such as nylon to reduce friction between the tether and the walls of the mechanism during elevator operation.

The advantage of the gate cylinder is the ease of operation. The disadvantage is the wear that occurs between the cylinder walls and tether.

#### 34.4 Dead Bolt

The Dead Bolt is again similar to the Slide Lock mechanism, however the hook procedure is accomplished by pulling the dead bolt down which allows the tether to pass within the mechanism. Finally, the releasing of the dead bolt will capture the tether within the mechanism. The

# SLIDE LOCK HOOK / UNHOOK MECHANISM



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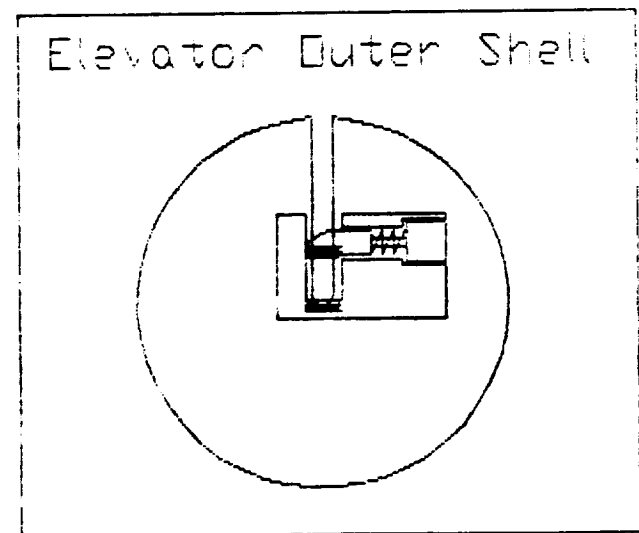
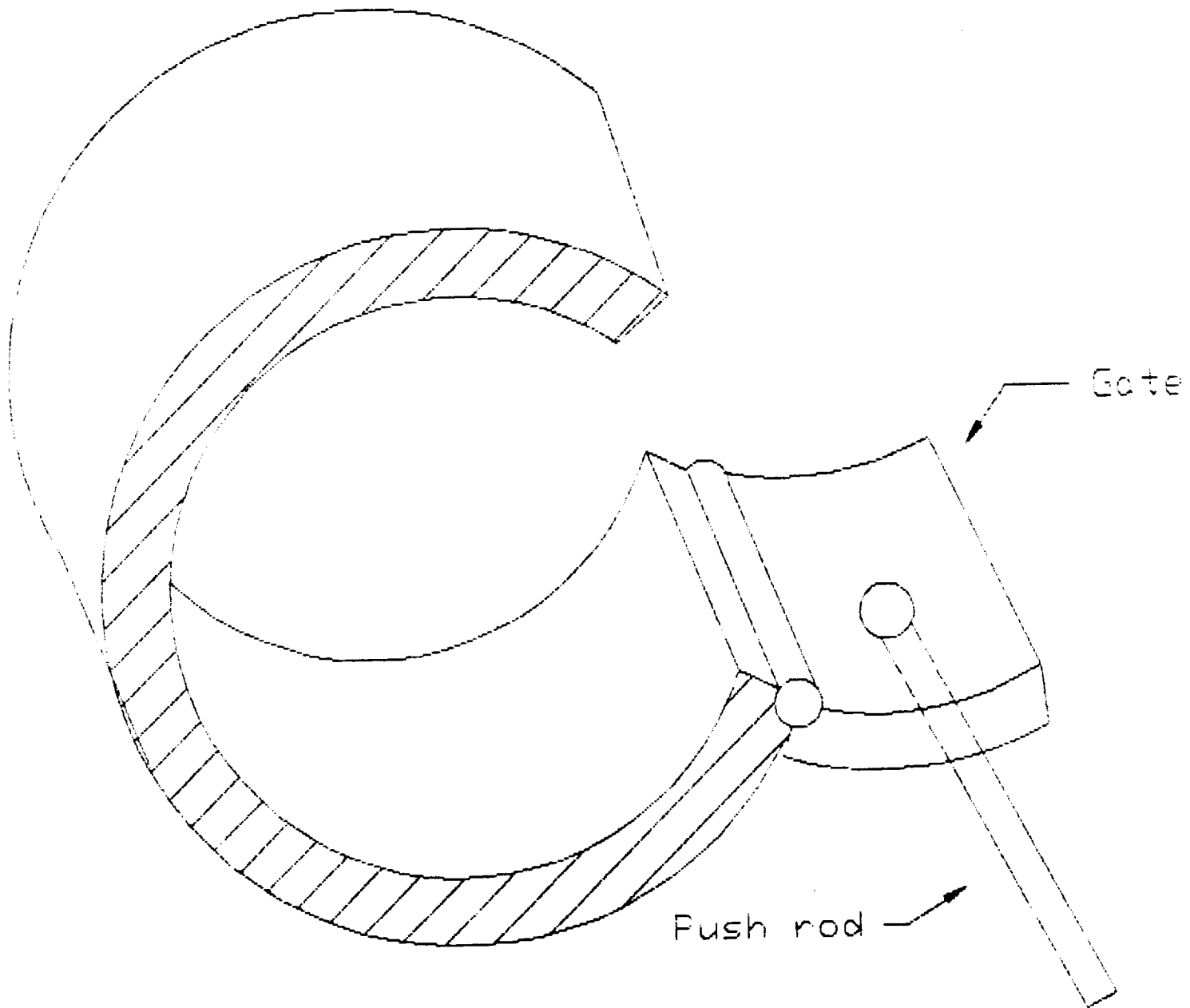


Figure 3.29

**CYLINDER GATE  
HOOK / UNHOOK MECHANISM**



**Figure 3.30**

pulling action on the dead bolt will be performed by a solenoid attached behind the bolt. A spring placed behind the bolt will allow the bolt to be pushed to its locking position. The unhook procedure is carried out simply by pulling the bolt down by the solenoid, thus releasing the tether from the elevator. Also, the roller guides are placed on the left and right sides of the locking mechanism to reduce unnecessary wear on the tether. A diagram of the mechanism is given in Figure 3.31.

The advantages of the design is simplicity and ease of operation. Its major disadvantage is damage to tether that occurs if the tether is not properly placed within the mechanism when the bolt is released during hooking procedures.

#### 34.5 Locking Rings

Similar to the three ring binder found on most notebooks, the Locking Rings will close around the tether when guided by the guide mechanism. Once the tether is located in the center of the mechanism the two rings will snap shut around the tether causing it to be captured by the elevator. Unhooking is accomplished simply by opening the two ring binder. A diagram of the device is given in Figure 3.32.

The advantage of the design is the simplicity of design and ease of operation during the hook / unhook procedure. The disadvantage is that damage to the tether can occur if the tether is not located in the center of the mechanism. Also, the roller guides cannot be integrated with the device.[41]

### Chapter 35. Drive Mechanism

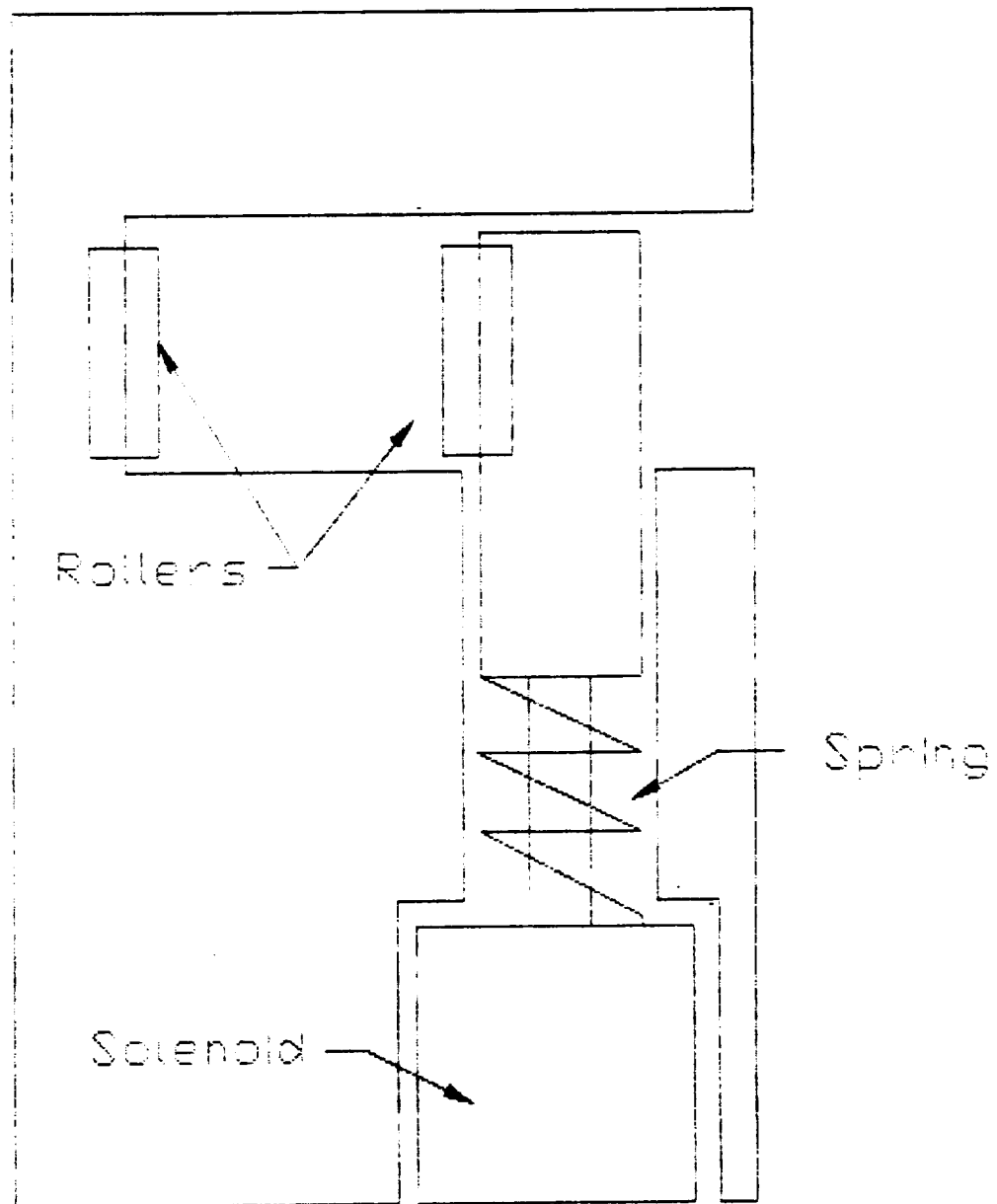
This chapter expands on the Bi-Wheel Friction Belt design which was proposed in Design Phase I. The following three variations of this design are being considered:

1. Bi-Wheel Friction Belt Single Drive
2. Bi-Wheel Friction Belt Dual Drive
3. Bi-Wheel Friction Belt Dual Drive With Regenerative Power Capabilities

These designs will be covered in more detail in the following sections.



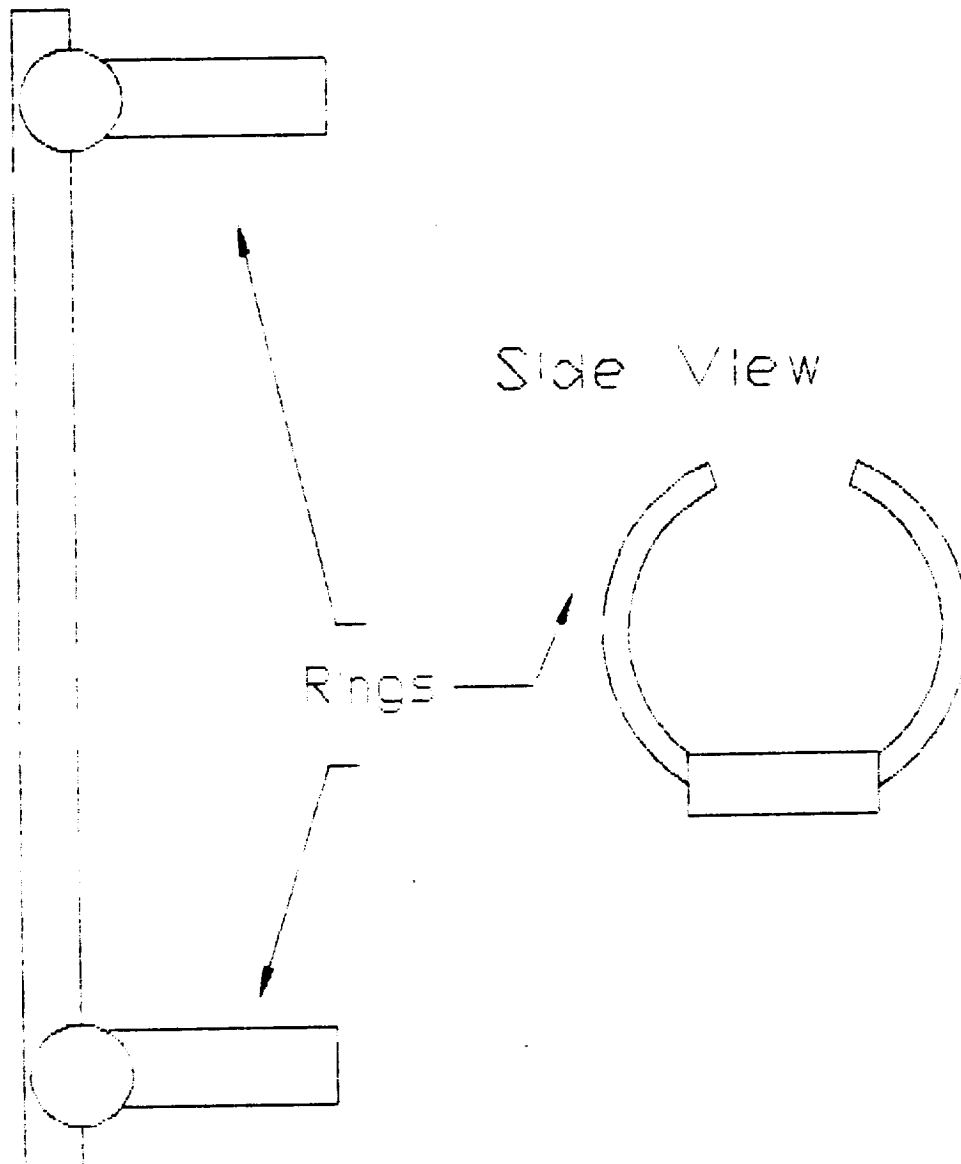
## ***DEAD BOLT HOOK / UNHOOK MECHANISM***



**Figure 3.31**

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# ***LOCKING RINGS HOOK / UNHOOK MECHANISM***



**Figure 3.32**

### 35.1 Single Drive Unit

The first of the Bi-Wheel Friction belt design considerations is that of the single drive unit shown in Figure 3.33. This drive mechanism consists of two drive wheels, two idler pulleys, two toothed drive belts, and a linear actuator. The two 4 inch diameter drive wheels are driven by D.C. motors which are monitored by tachogenerators to insure proper speed and position of the elevator. The linear actuator applies pressure to the drive belts forcing them to contact the tether which supplies the necessary friction required to traverse the tether.

This single drive unit would be placed in the center of the elevator with the tether entering the top of the unit and exiting through the bottom. The advantages of this single drive unit are its relatively small size, mass, and simplicity. The disadvantages are the lack of redundancy and the lack of stability due to the centrally located drive unit.

### 35.2 Dual Drive

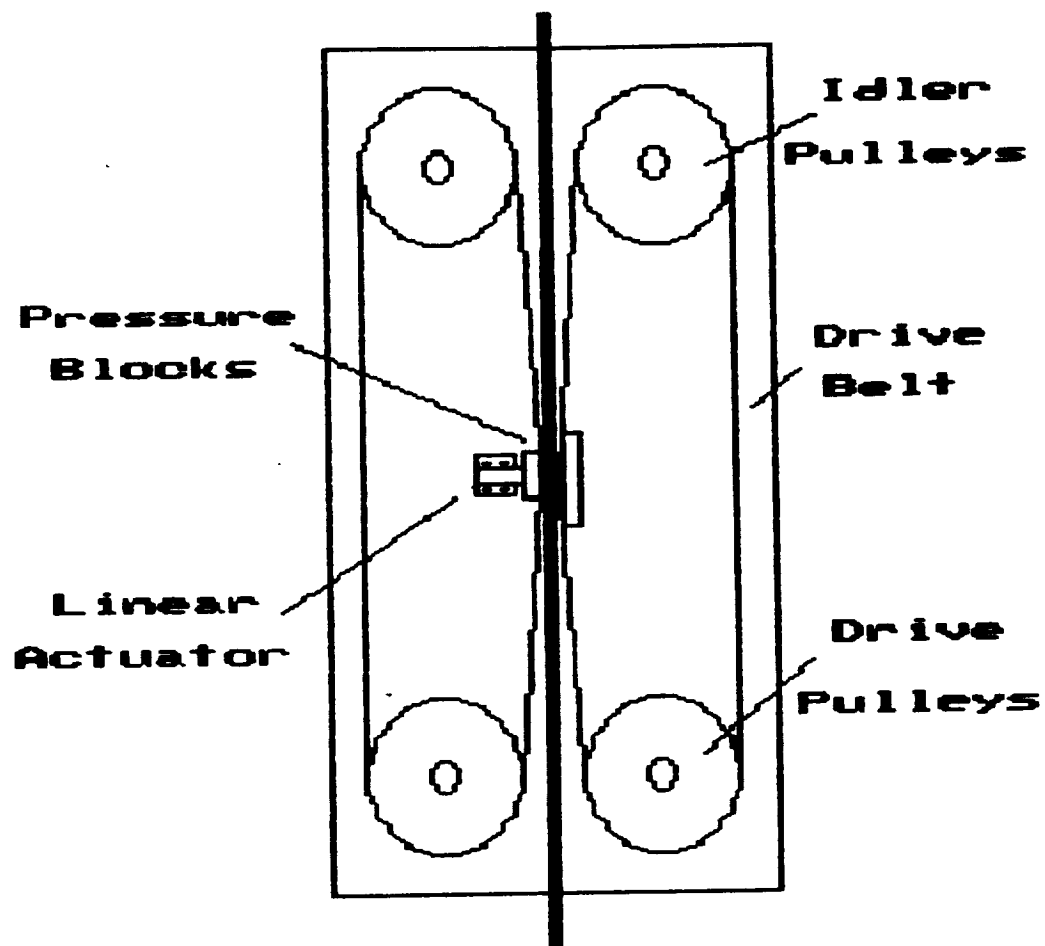
The second design consideration is that of a Bi-Wheel Friction Belt with two separate drive units as shown in Figure 3.34. This drive mechanism configuration consists of two independent drive units each consisting of two drive wheels, two idler pulleys, two toothed drive belts, and a linear actuator. Each of these independent drive units would operate in the same manner as the single drive unit.

One of these drive units is mounted near the top and bottom of the elevator. This drive configuration makes the elevator system more stable and provides backup drive mechanisms. The disadvantages of this configuration are added cost, mass, and complexity.

### 35.3 Dual Drive With Regenerative Power

The last of the Friction Belt design considerations is that of dual drive units with regenerative power capabilities shown in Figure 3.35. This drive mechanism configuration consists of two independent drive units each consisting of two drive wheels, two generator wheels, two toothed belts, and a linear actuator. These drive units differ from the other drive units by the placement of regenerative motors instead of the idler pulleys. This allows the generation of power during operation of the elevator. Although the regenerated power is an advantage, it increases the mass and complexity, which are disadvantages.

# ***SINGLE DRIVE BI-WHEEL FRICTION BELT DRIVE MECHANISM***



**By Group 3 Fall 1988**

**Figure 3.33**

# *DUAL DRIVE BI-WHEEL FRICTION BELT DRIVE MECHANISM*

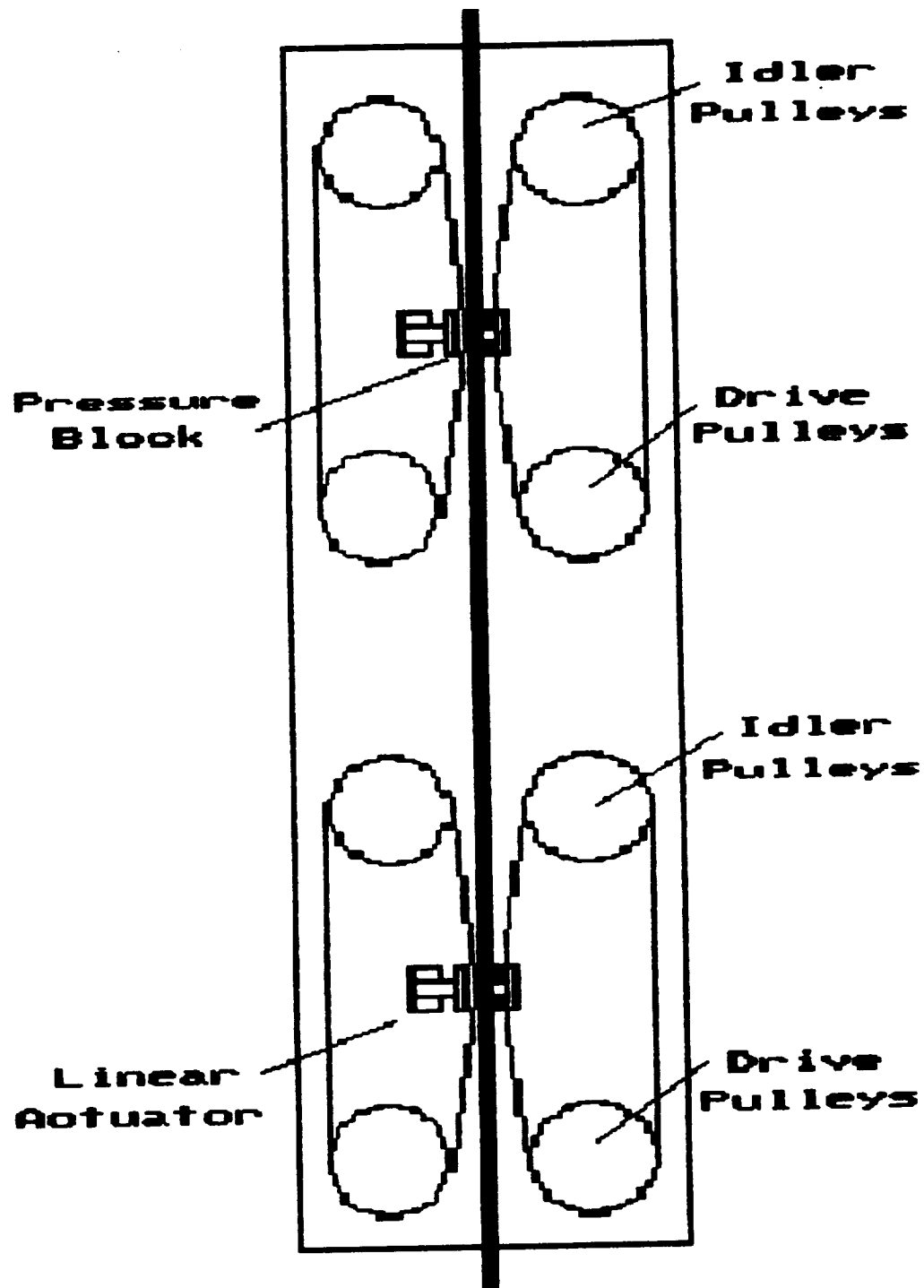


Figure 3.34

**DUAL DRIVE BI-WHEEL FRICTION BELT  
DRIVE MECHANISM W/ REGENERATIVE MOTORS**

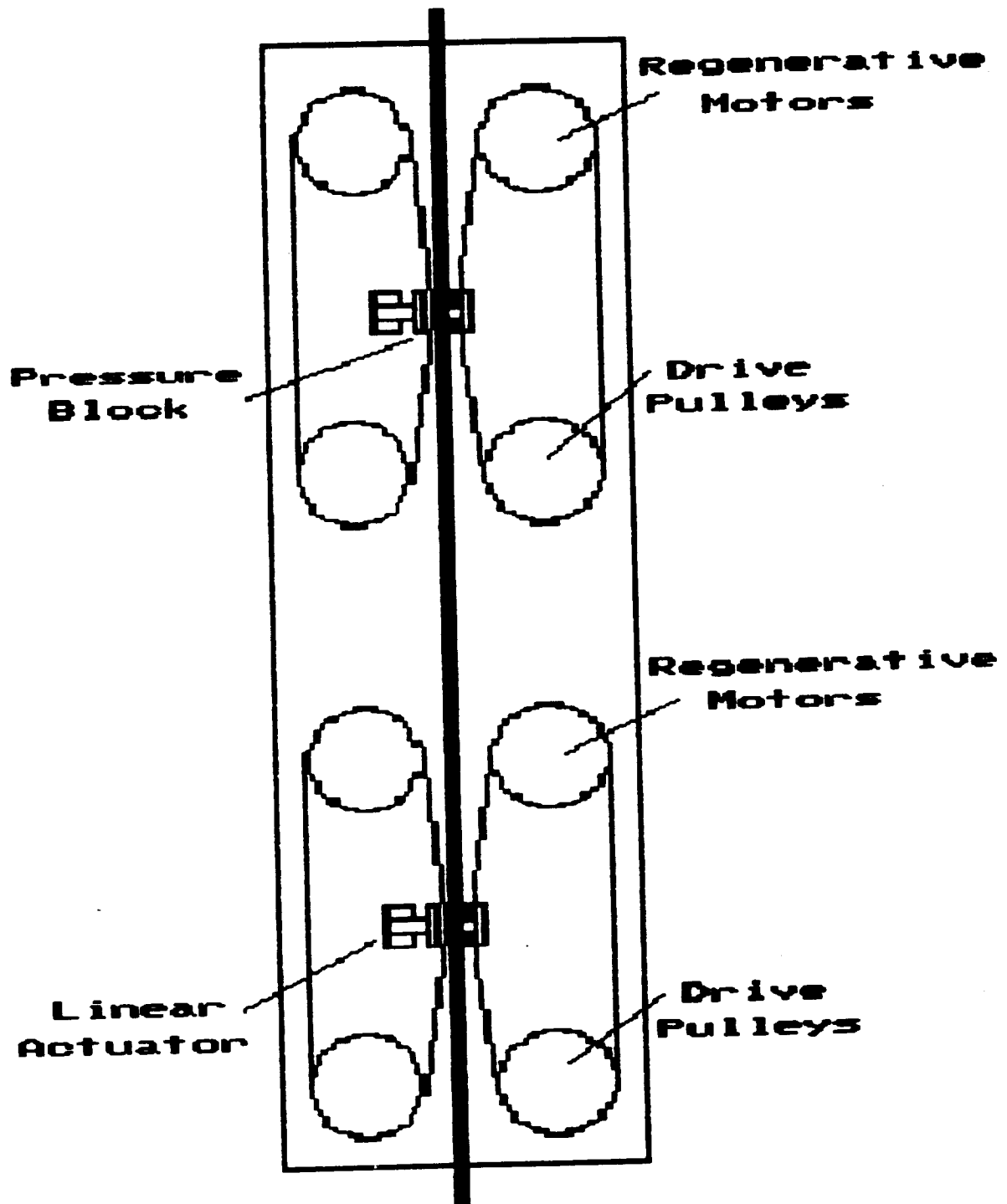


Figure 3.35

## Chapter 36. Sliding Block / Friction Belt Interface

The sliding block / friction belt interface is located at the pressure blocks and is an area of high friction and heat generation. These pressure blocks must provide constant pressure to the friction belts while not damaging them in any way. The following designs are being considered in this section:

1. Roller Surface
2. Self-Lubricating Surface

### 36.1 Roller Surface

The first of the pressure block designs is that of a roller surface shown in Figure 3.36. This configuration consists of pressure blocks with small rollers or needle bearings on the contacting sides.[35] The disadvantages of this design is the detailed machining of the small rollers and pressure is only applied at roller locations.

### 36.2 Self-Lubricating Surface

The other pressure design is that of a self-lubricating surface shown in Figure 3.37. This design consists of pressure blocks coated with an ablative material. This material can be a sacrificial material which wears and lubricates the surface thus preventing damage to the belt. The advantages are no moving parts and even pressure over the entire surface of the pressure blocks. A disadvantage is the frequent replacement of the pressure blocks.

## Chapter 37. Braking Mechanism

The braking mechanism is perhaps the most critical component of the LEOTAD. It must function with extreme reliability and accuracy. A brake failure could cause an accident of catastrophic proportions. The following design constraints shall be incorporated or allowed for in the design of the braking mechanism.[42]

- \* a redundancy in backup systems will have to be incorporated for safety,
- \* the braking mechanism must operate effectively and efficiently in either direction. It must be able to brake the LEOTAD at a constant acceleration under/during gravitational gradient conditions,
- \* the braking mechanism should be able to provide an alternative source of power for the LEOTAD during its actuation,

## *PRESSURE BLOCKS WITH ROLLER SURFACE*

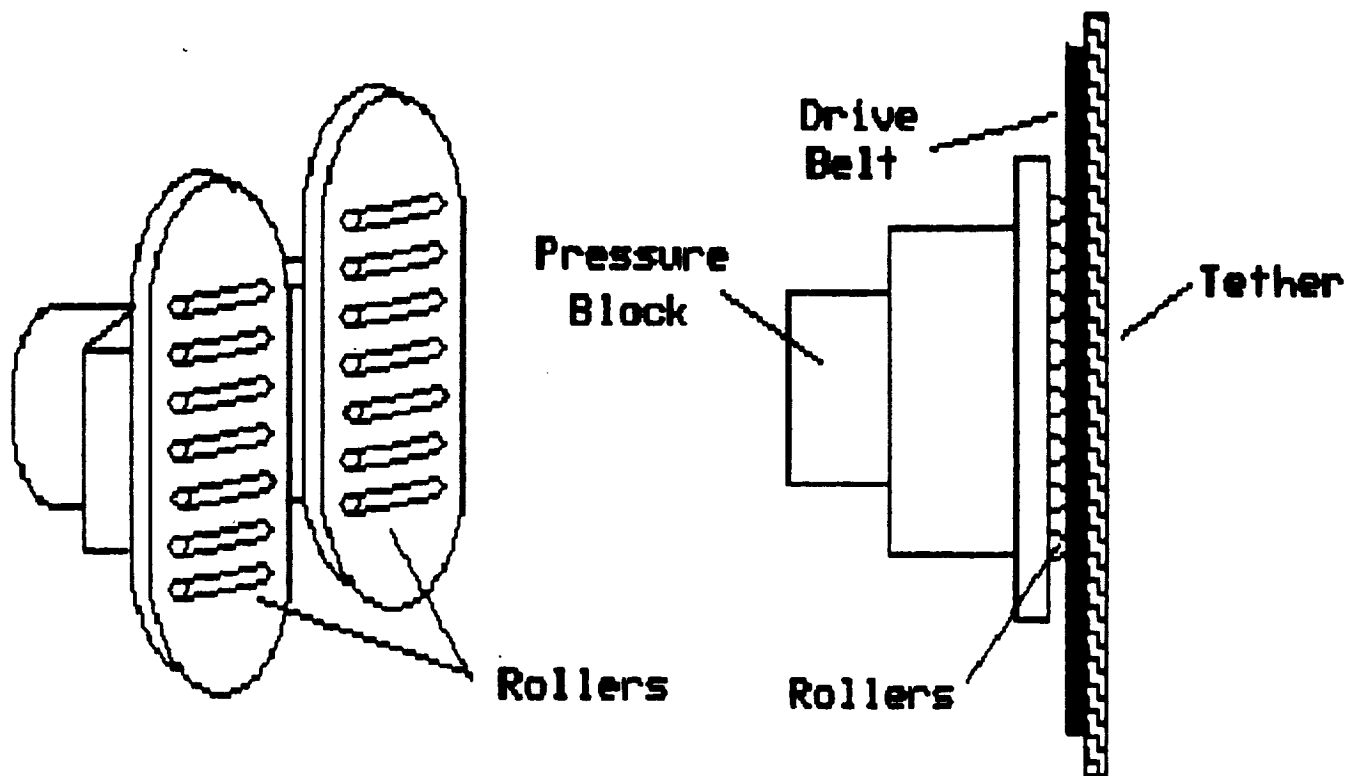


Figure 3.36

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***PRESSURE BLOCKS WITH  
SELF-LUBRICATING SURFACE***

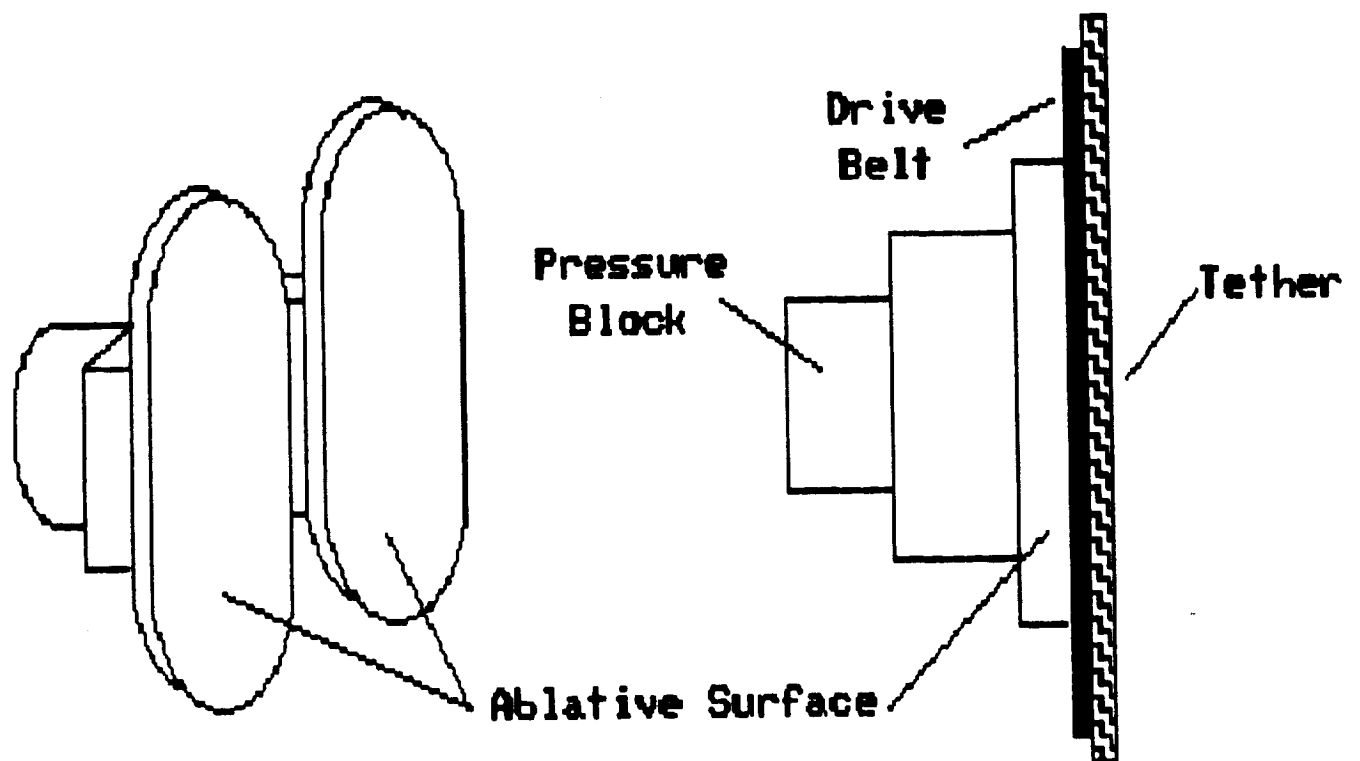


Figure 3.37

- \* the braking system must operate in temperatures ranging from -250 to +250 degrees Fahrenheit,
- \* the braking system should have a 20 year life span,
- \* the braking mechanism must be able to overcome all gravity gradient forces exerted on the LEOTAD,
- \* the braking system must operate both dependently and independently of the drive mechanism.

The maximum gravity gradient force encountered by the LEOTAD, loaded or unloaded, can be determined from the following equation.[41]

$$F_{gg} = 3Lmw^2$$

where

$$w^2 = GM/R^3$$

L = distance from the center of gravity of the tethered system to the LEOTAD, (maximum distance is 10 km)

m = mass of the LEOTAD and its payload, (assumed to be a maximum of 25000 kg)

G = Universal Gravitational Constant,  $(6.673 \times 10^{-11} \text{ Nm}^2/\text{kg}^2)$

M = mass of Earth,  $(5.979 \times 10^{24} \text{ kg})$

R = LEOTAD orbit radius, (about 4200 miles)

Using these equations and assuming a maximum LEOTAD mass of 25000 kg, which includes two Space Shuttle pallets and the payloads contained in the pallets, a maximum gravity gradient force can be found. The maximum gravity gradient force occurs when the LEOTAD is at the end mass and is roughly 1000 N. For an unloaded LEOTAD the maximum gravity gradient force is about 200N for a 5000kg LEOTAD at the end mass.[41] Of course there are many more constraints and specifications that must be considered for the design of the braking mechanism.

Five methods of braking shall be presented as well as one positive hold brake method. It should not be misconstrued that since only one positive hold method is being presented there are no alternative positive hold configurations. All other braking methods introduce redundancies in positive holding capabilities. The five basic configurations are as follows:

1. Disk / Caliper Brakes
2. Drum / Shoe Brakes
3. Regenerative / Reverse Motor Brakes

4. Cold Gas Jet Braking[43]
5. Direct Tether Contact Positive Hold

The frictional force required to stop the LEOTAD is equivalent to the maximum gravity gradient force. With this information and a value for the coefficient of friction of the braking materials, the normal force required of the braking system can be determined:

$$\text{Normal force} = (\text{frictional force})(\# \text{ of interfaces})/(\text{coef. of friction})$$

where

frictional force = 1000 N, (the max. gravity gradient force),  
 coef. of friction = 0.3, (this is an approximation assumed from sliding contact of asbestos on steel).[44]

### 37.1 Disk / Caliper Brakes

There are three basic configurations of disk brakes which can be implemented. Each may use an electrically or hydraulically actuated caliper which would apply friction to the disk or rotor via a friction pad. The basic configurations are:

1. the drive / idler pulley as the rotor (PR), Figure 3.38,
2. a rotor extended from the drive / idler pulley, i.e. extended rotor (ER), Figure 3.39,
3. a rotor connected to a drive shaft extended from the rear of the drive motor, i.e. extended rear shaft rotor (ERSR), Figure 3.40.

Disk brakes are the preferred method of braking in the auto industry. There are usually fewer moving parts and increased pressures that can be exerted to the rotor by the caliper. Smooth and even braking is inherent with the design. These characteristics may or may not change under microgravity conditions. Due to this question tests need to be made under simulated microgravity conditions to determine their characteristics. Also the rotor may be a possible heat radiator when not used for braking since heat dissipation from the LEOTAD may be a concern. These advantages apply to all disk configurations. The PR would take up less space and have less mass than the ER or the ERSR; efficient use of space and mass is very important in the LEOTAD.

Using the drive or idler pulleys as a rotor, as in the PR, may produce increased temperatures that would damage or

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## *PULLEY ROTOR BRAKING MECHANISM*

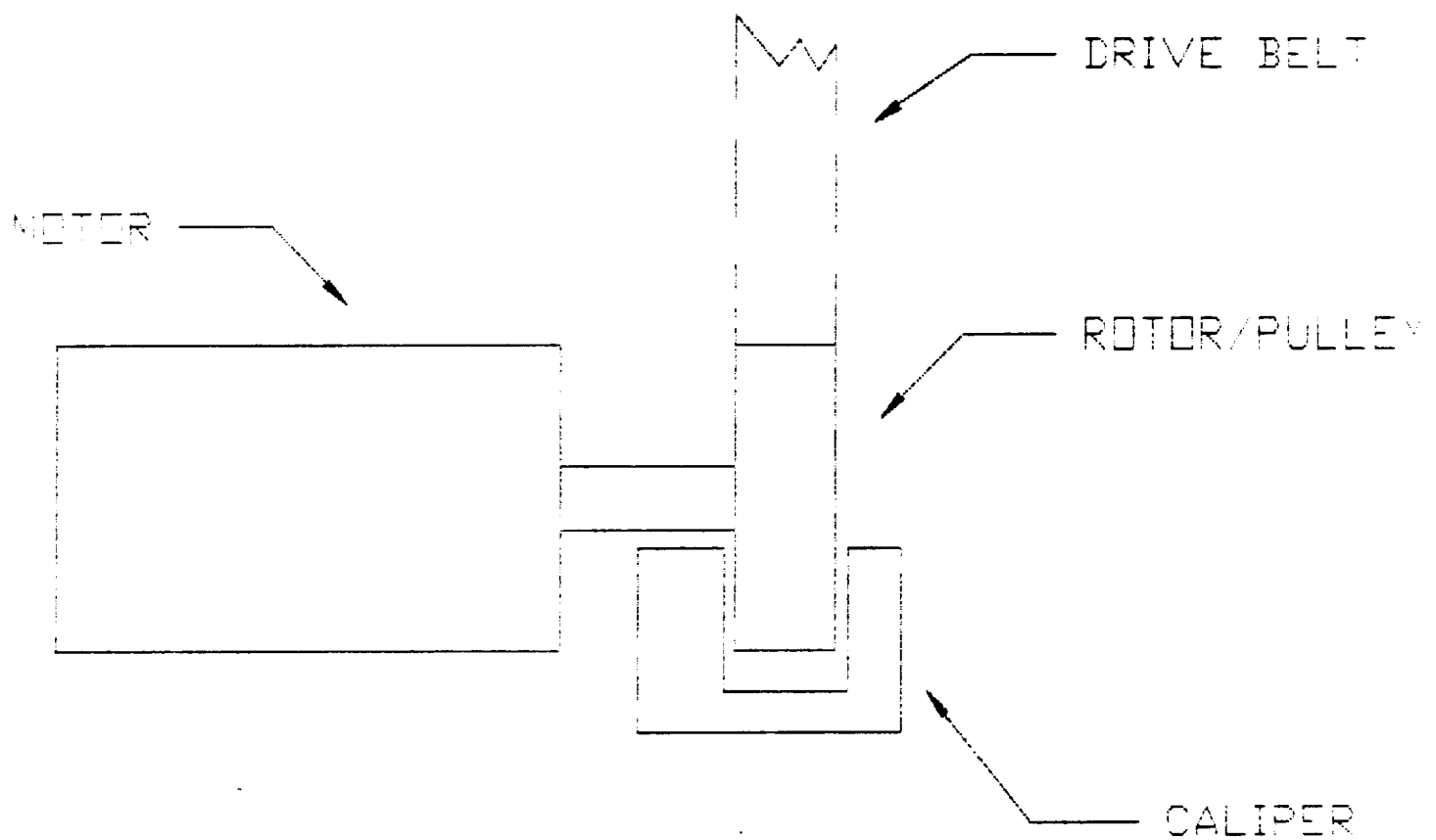


Figure 3.38

## EXTENDED ROTOR BRAKING MECHANISM

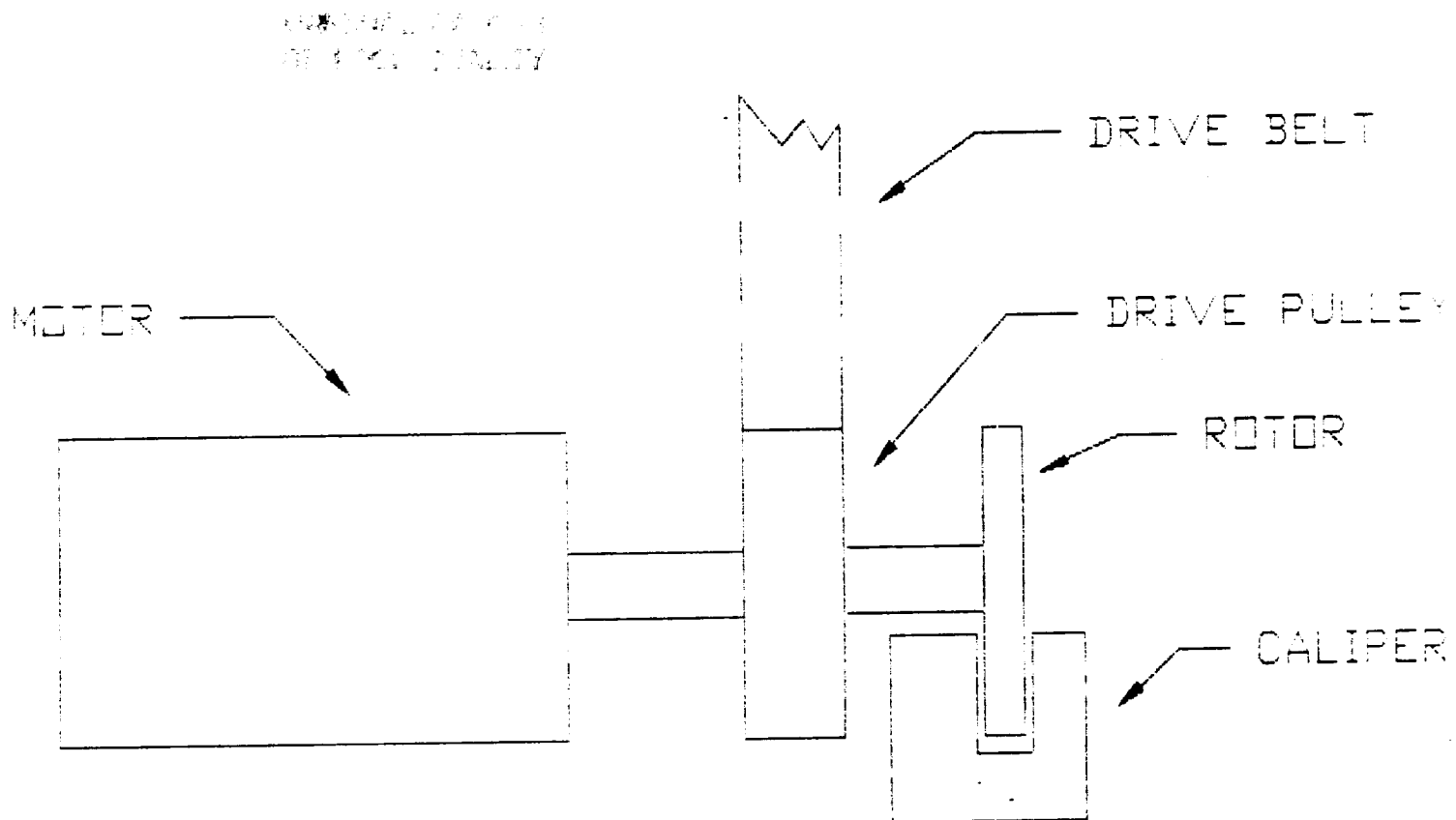
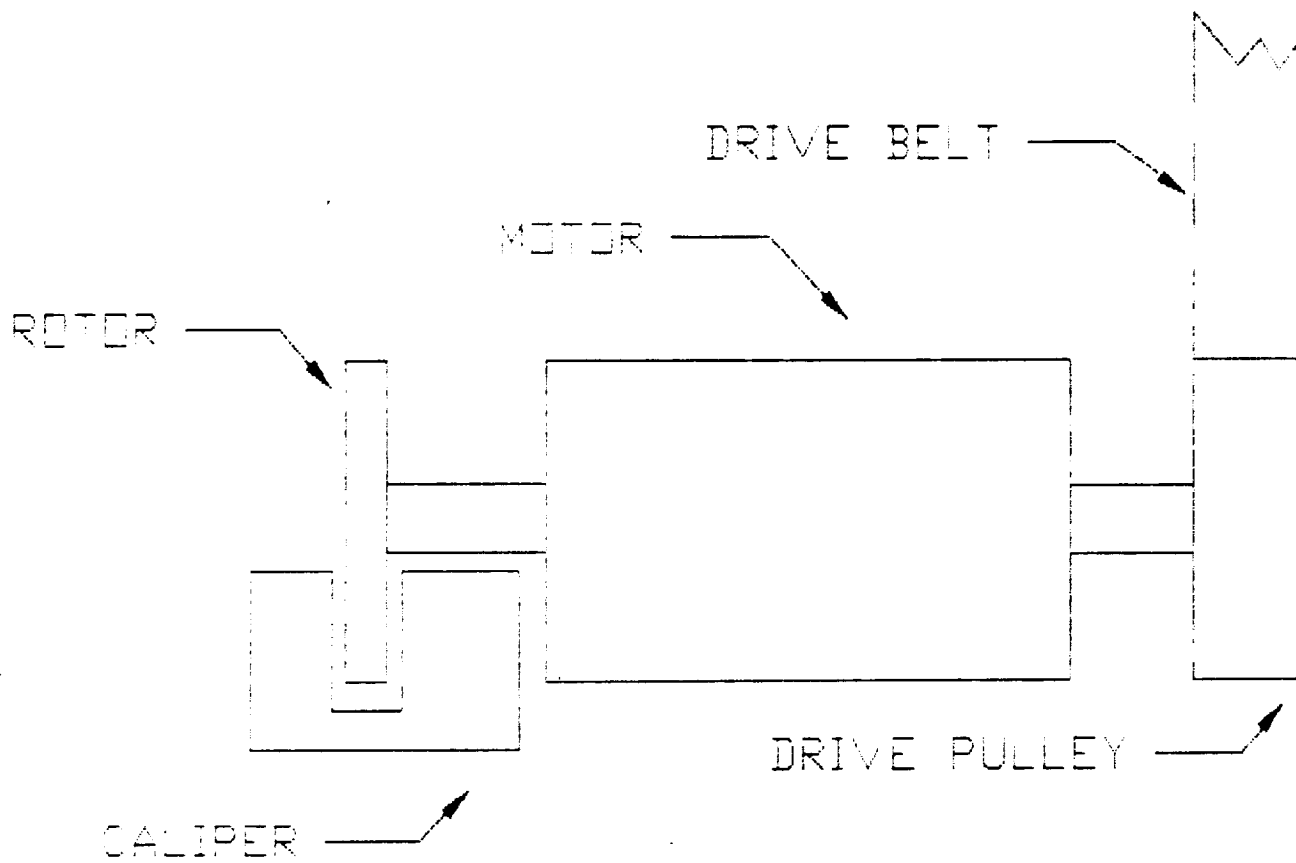


Figure 3.39

# ***EXTENDED REAR SHAFT ROTOR BRAKING MECHANISM***

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**Figure 3.40**

shorten the life of the drive belt. Also, the PR probably could not be used for heat transfer purposes. The increased mass of the ER and ERSR may be undesirable.

### 37.2 Drum Brakes

The drum configurations are implemented in the same manner as the disk brake configurations. A typical drum and friction shoe arrangement is shown in Figure 3.41. The drum configurations are as follows:

1. the drive/idler pulley used as the drum (PD), Figure 3.42
2. a drum extended from the drive/idler pulley, i.e. extended pulley drum (ED), Figure 3.43
3. an extended rear drive shaft drum (ERSD), Figure 3.44

The advantage or disadvantage of drums over rotors is not apparent at this time as no tests of the different methods under simulated microgravity conditions have been performed. The ED and ERSR configurations may be used for heat dissipation.

The same disadvantages which apply to the disc / caliper configurations also apply to the respective drum brake configurations.

### 37.3 Direct Tether Positive Hold

The positive hold (PH), Figure 3.45, would be used as an emergency brake and only applied when the LEOTAD is not translating along the tether. It is essentially a ratchet lock that cinches down on the tether thus eliminating movement in the direction of PH orientation. The PH would incorporate a deactivating solenoid to fail safe the actuation of the PH during tether translation of the LEOTAD. The PH would preclude any slipping of the LEOTAD during robotic arm operation or disturbances not accounted for in the LEOTAD design.

The PH would be another source of tether wear since it is in direct contact with the tether. The deactivation solenoid system would have to be extremely reliable since PH activation during the LEOTAD translation could cause stresses in the tether sufficient to break it.

## *BRAKE DRUM ASSEMBLY*

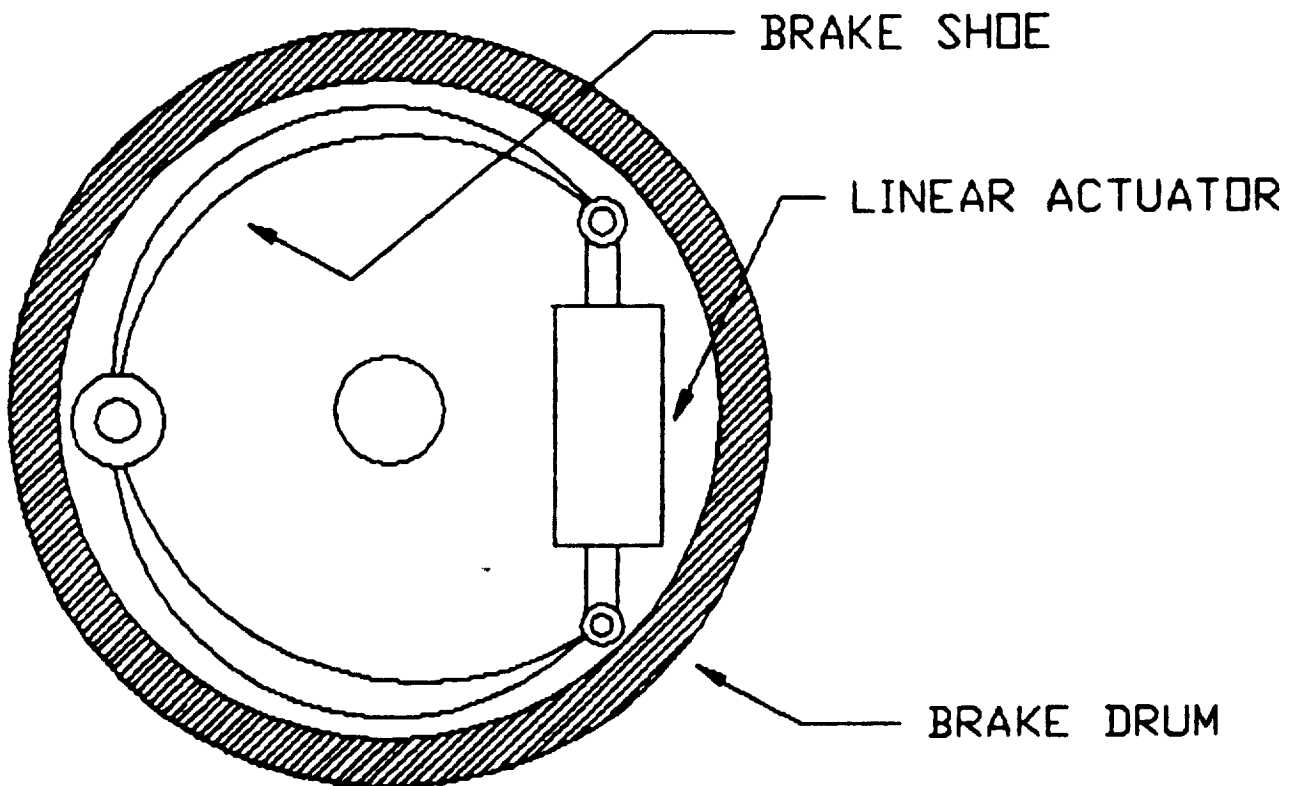
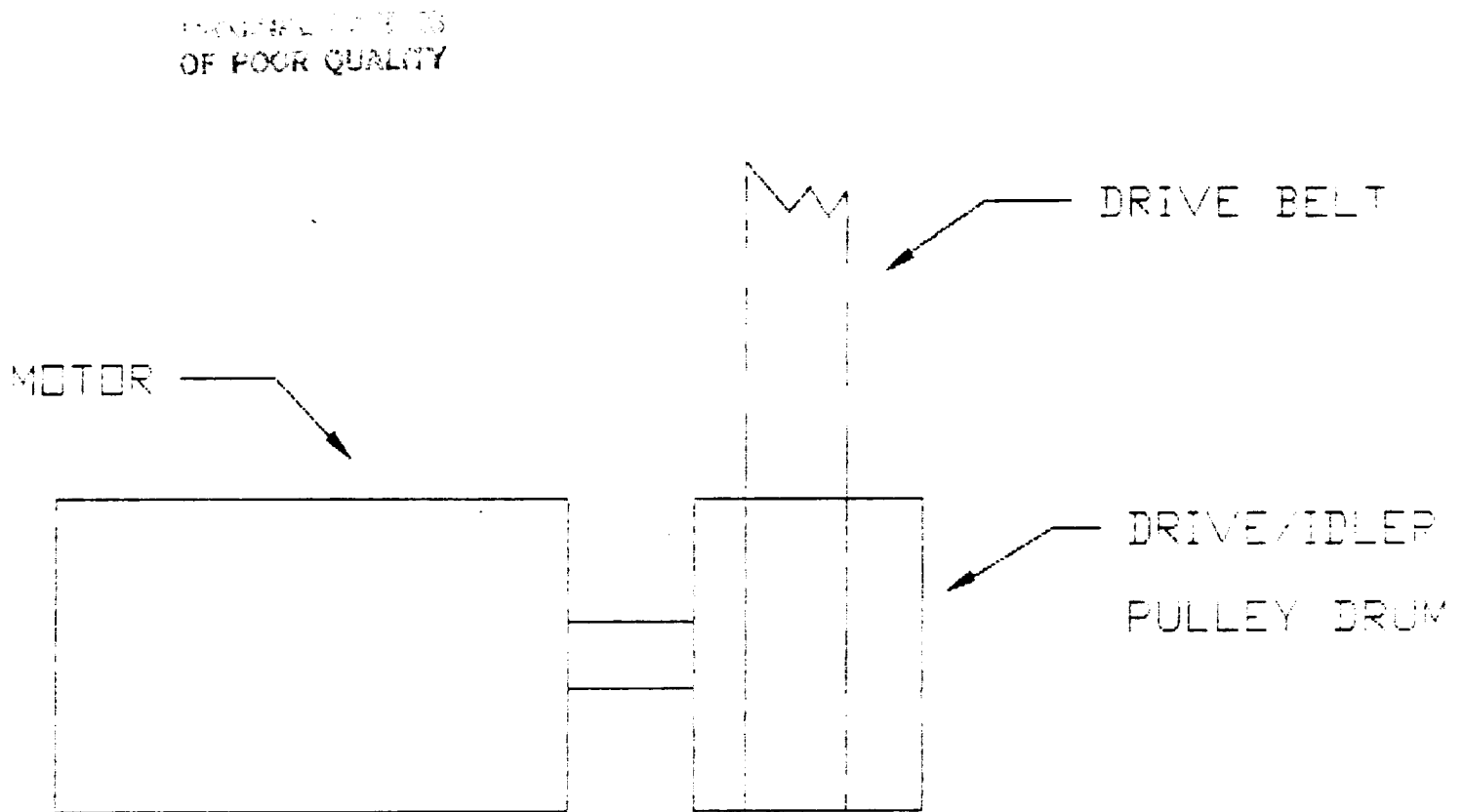


Figure 3.41



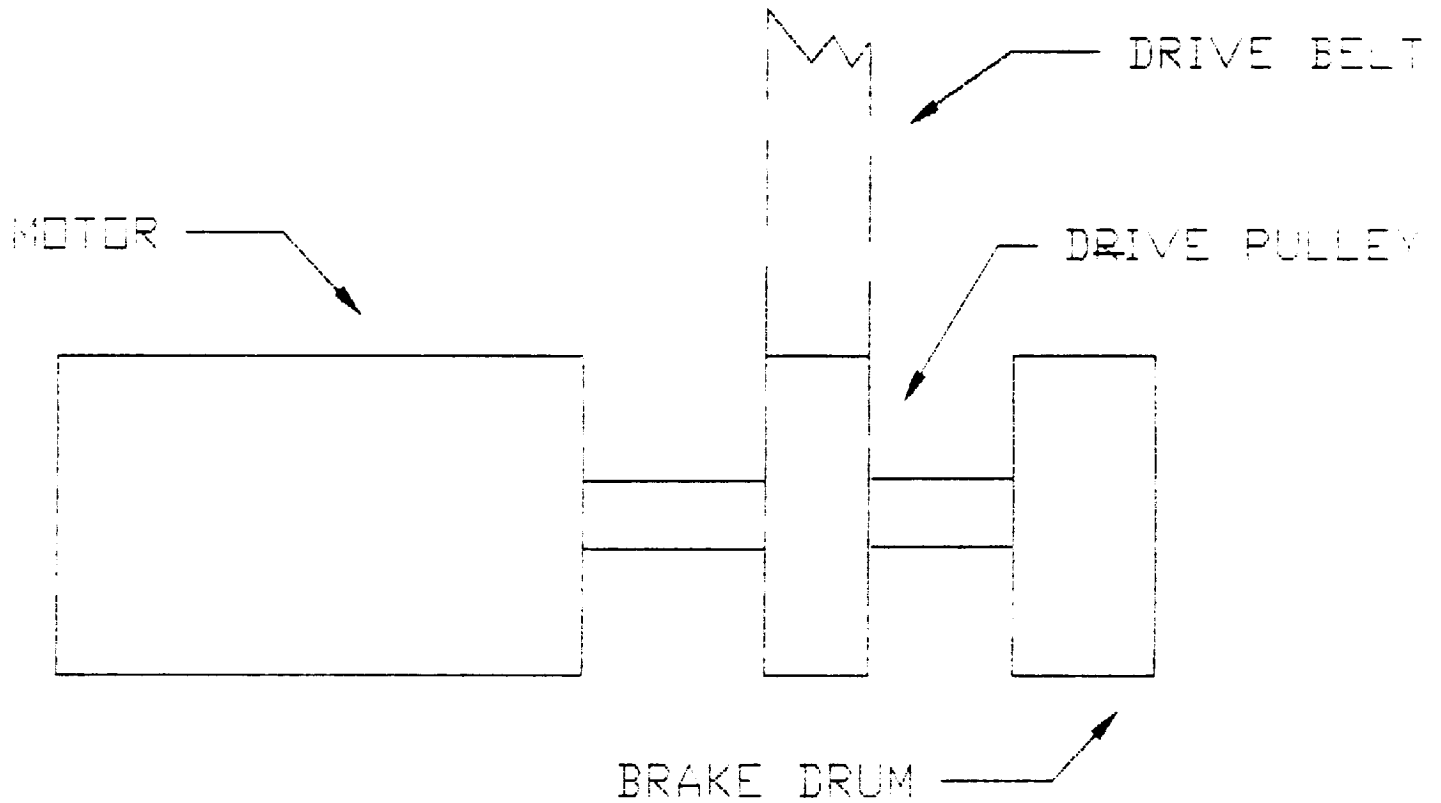
## ***PULLEY DRUM BRAKING MECHANISM***



**Figure 3.42**

## ***EXTENDED DRUM BRAKING MECHANISM***

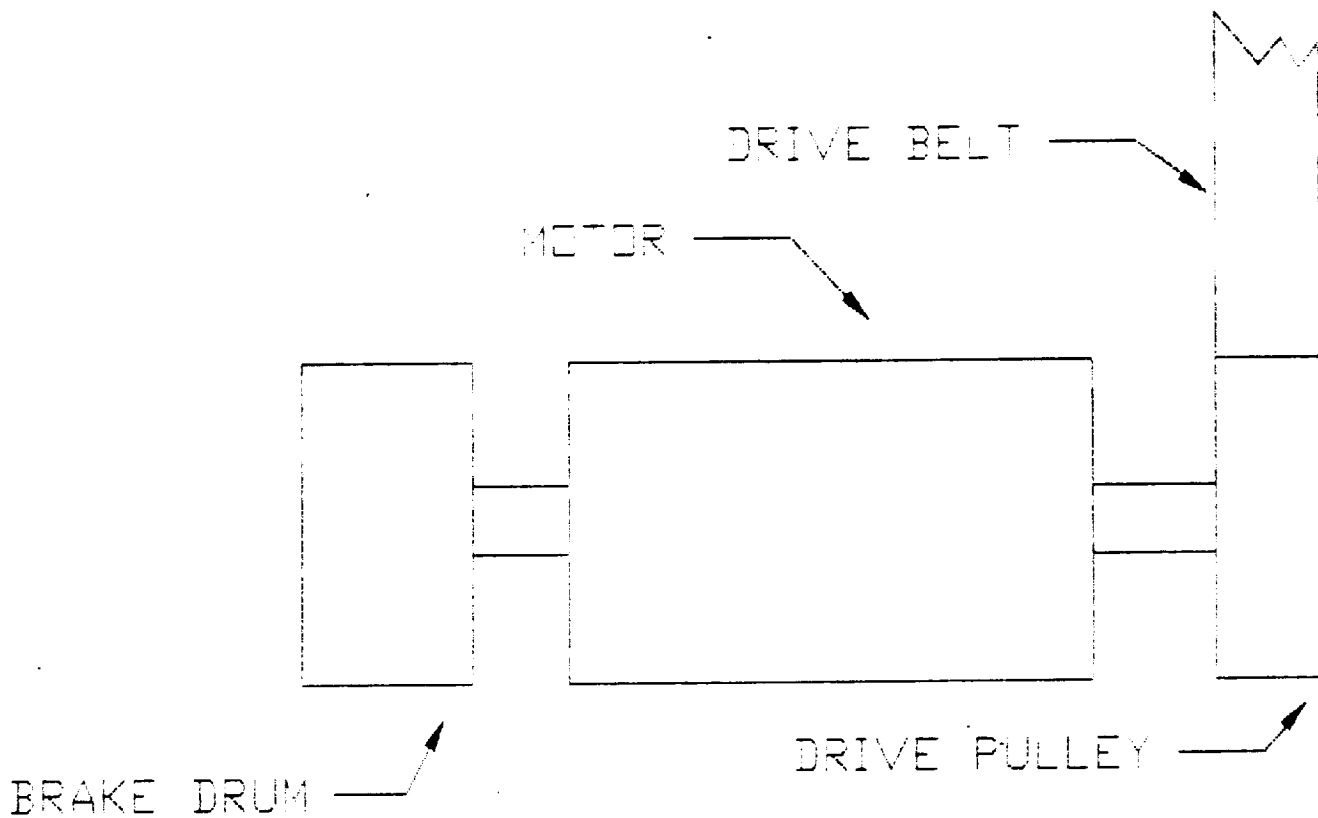
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**Figure 3.43**

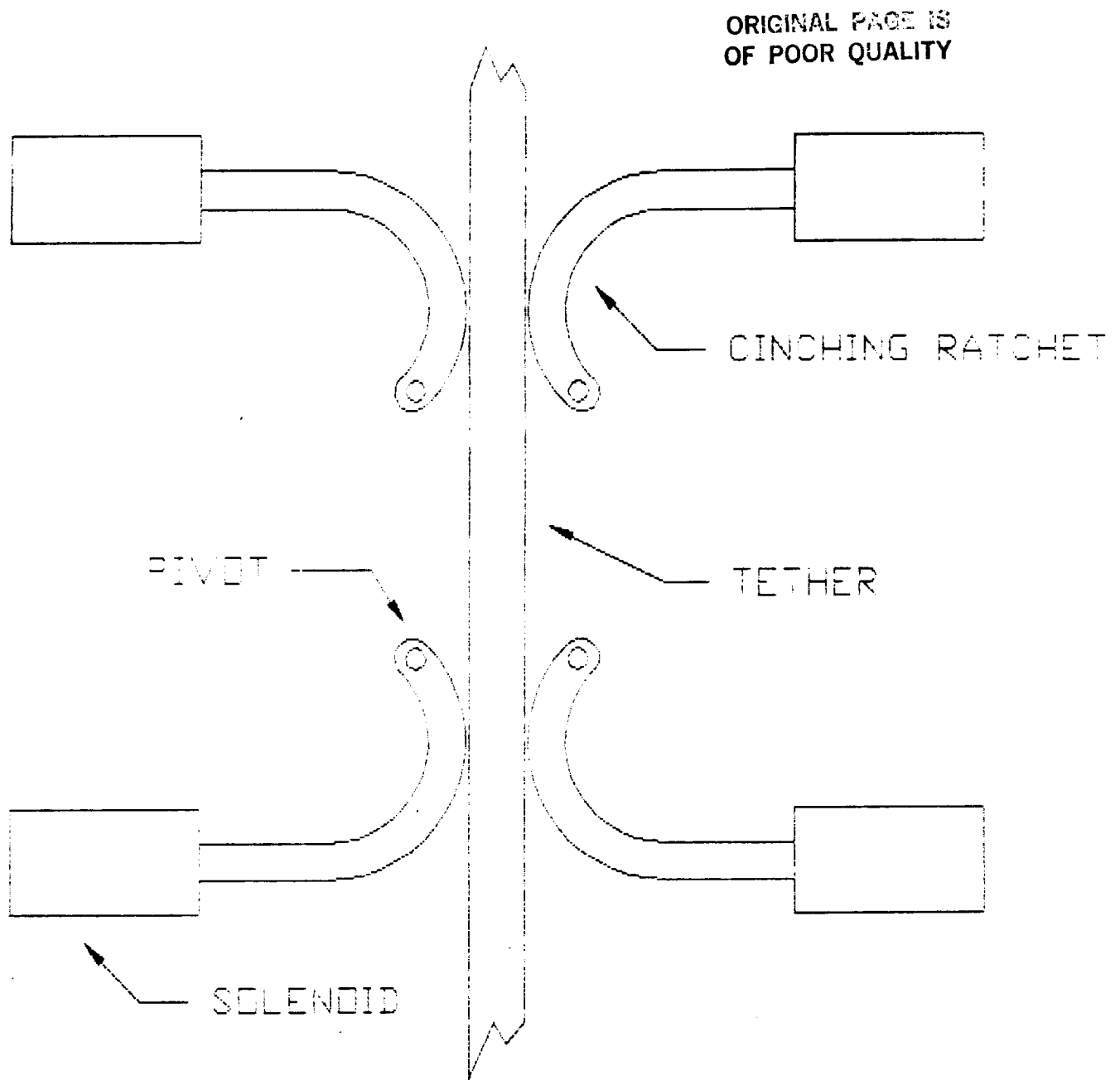
# ***EXTENDED REAR SHAFT DRUM BRAKING MECHANISM***

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**Figure 3.44**

## ***DIRECT TETHER POSITIVE HOLD BRAKING MECHANISM***



**Figure 3.45**

#### 37.4 Regenerative Motor Braking

In the event that DC motors are used, and this seems likely, electricity may be generated from the motors and maintain constant velocity during gravity gradient force interaction on the LEOTAD. This may be a very attractive method of power generation and braking since the same hardware is used for both purposes. Power is generated during braking through the use of one system, thus the hardware, and the space occupied by it, are used efficiently. No extra mass would be introduced to the LEOTAD to achieve this.

It is not known at this time if sufficient power generation can be achieved by this method or if sufficient braking will be produced. It is suspected that regenerative braking along with another method will be necessary to produce the amount of braking needed for safe control of the LEOTAD during gravity gradient force interaction. In addition to this, an added disadvantage of accelerated wear on the drive motors may occur.

#### 37.5 Cold Gas Jet Braking

Cold gas jets are used extensively on spacecraft and, therefore, little research would be necessary to implement such a system on the LEOTAD. Orbital maneuvering systems (OMS pods) currently used on the Space Shuttle are based on cold gas jets.[43]

Cold gas jets are extremely reliable and can offer very gentle transitions in velocity.

Cold gas jets require reservoirs of compressed gas which would require periodic refills to maintain operational status. The time intervals between reservoir recharge may be preclusively short. Alternatively, reservoirs of a volume sufficient to avoid frequent recharges may demand too much space in the LEOTAD or may be too massive.

### Chapter 38. Materials

There were several components of LEOTAD that needed material analysis. Of course all components must withstand the extreme environmental conditions of LEO, but we only investigated materials concerning the tether, drive belts, tension adjustor, and drive belt / sliding block interface.

Tether technology for space applications is a fairly new area of research. Space tether technology was first begun by Material Concepts, Incorporated which was contracted by NASA

in December 1984.[45] Material Concepts, Inc., now Fiber Materials, Inc., metal coated Kevlar and other samples for possible candidates for space tethers. Prior to this research candidate space tethers consisted of two components: a strength member (usually Kevlar) with a conductive core (a copper wire).[46] In this first phase of work, called NASA Phase I SBIR Project, six tethers were processed, tested, and evaluated by Fiber Materials, Inc. The samples were metal coated and identified as follows:[45]

- \* Sample 1: Copper coated Kevlar 49
- \* Sample 2: Nickel coated Kevlar 49
- \* Sample 3: Copper coated Kevlar 49 with a polyalloy (boron, tungsten, nickel) overcoat
- \* Sample 4: Copper coated Kevlar with a nickel overcoat
- \* Sample 5: Copper coated Kevlar with a Kel-F-800 overcoat
- \* Sample 6: Copper coated Kevlar 49 with a nickel overcoat and a Kel-F-800 overcoat over the nickel

After these samples were produced, five inch test specimens were exposed to a simulated atomic oxygen environment by placing them in NASA's Marshall Space Flight Center oxygen plasma chamber for five minutes. These samples were then tested visually (microscopic and Scanning Electron Microscope) and analytically for conductivity, mass loss (oxidation), and tensile strength. Tabulated data of before and after exposure follows. (Tables 3.1-3.3)

Samples five and six showed the most promising results, but since Kel-F-800 is not the optimum polymeric insulating coating, Sample 4 (copper with nickel overcoat) was selected as the optimal prototype tether in this initial investigation. The copper coat was approximately 0.95 microns (for conductivity) and the nickel was approximately 0.05 microns (to protect the copper from oxidizing). These preliminary results looked promising for NASA so they extended the contract calling it Phase II.

Fiber Materials, Inc. choose the one micron coating of Kevlar 49 as the core for three prototype space tethers in Phase II. A thousand feet of each prototype was produced and subjected through the same tests as before to test for breakload strength, electrical resistivity, and oxidative properties. The three samples follow:[45]

- \* Sample 1: 1000 feet of metal coated Kevlar, 8 tows (8000 filaments) in a parallel lay, overbraided with a tight Nomex jacket

## CONDUCTIVITY OF SAMPLES BEFORE AND AFTER OXYGEN EXPOSURE

<u>SAMPLE/COATING(S)</u>	<u>RESISTANCE, OHMS/5" *</u>	
	<u>BEFORE EXPOSURE</u>	<u>AFTER EXPOSURE**</u>
1 - Cu	0.4 - 0.5	3.0
2 - Ni	2.2	2.0
3 - Cu/Polyalloy	11.3 - 12.5	140.0
4 - Cu/Ni	0.2 - 0.3	0.3
5 - Cu/KEL-F-800	5.1 - 8.0***	32.0***
6 - Cu/Ni/KEL-F-800	1.2***	0.4***

NOTES:      \* - Measured with a standard multimeter

             \*\* - Exposure to oxygen plasma for 5 minutes at  
                         approximately 900 microns

             \*\*\* - Measured through the polymer coating (i.e., coating  
                         was not stripped away)

Table 3.1

## MASS LOSS IN EXPOSED SAMPLES

SAMPLE/COATINGS	TOTAL METAL COATING THICK- NESS, MICRONS	MASS LOSS AFTER EXPOSURE, MG/IN	% MASS LOSS
1 - Cu	0.7	0.92	8.7
2 - Ni	1.6	1.60	8.0
3 - Cu/Polyalloy	0.7	2.50	24.0
4 - Cu/Ni	1.3	1.90	13.0
5 - Cu/KEL-F-800	0.7	0.14	1.0
6 - Cu/Ni/KEL-F-800	1.3	0.52	2.8

Table 3.2



## SAMPLE TENSILE DATA

SAMPLE NUMBER	BEFORE EXPOSURE*			AFTER EXPOSURE			% CHANGE
	LOAD, lbs.	STRESS, psi	% STRAIN	LOAD, lbs.	STRESS, psi	% STRAIN	
1	47	33813	0.187	-	-	-	-
2	74	53237	0.296	-	-	-	-
3	68	48921	0.271	-	-	-	-
4	64	46043	0.256	-	-	-	-
5	61**	43885	0.244	32**	230022	0.128	52.0
6	58**	41727	0.232	34**	24460	0.136	58.6

NOTES:   \* - AVERAGE OF THREE TESTS

     \*\* - NO EPOXY USED

Table 3.3

- \* Sample 2: 1000 feet of metal coated Kevlar, 8  
tows in a parallel lay, extruded with  
Teflon and overbraided with a tight  
Nomex jacket
- \* Sample 3: 1000 feet of metal coated Kevlar, 3  
tows (3000 filaments) in a parallel  
lay, overbraided with a tight Nomex  
jacket

Electrical resistances for the three sample prototypes were as follows: Sample 1, 0.07 ohm/ft; Sample 2, 0.058 ohm/ft; Sample 3, 0.208 ohm/ft. Breakload values for the three were 333.0, 368.3, and 175.6 pounds, respectively.[45]

To test for oxidation the NASA-Marshall Plasmoid chamber was once again utilized. Samples of each prototype were subjected to both short-term and long-term exposures. The short-term exposure consisted of five minutes while the long-term exposure consisted of one hour.

Average mass losses for the short-term exposures were 1.67, 1.12, and 3.09 percent. The long-term exposures revealed 14.6, 9.5, and 30.2 percent mass losses.[45]

Samples 1 and 3 showed relatively the same microscopic results. No damage for short-term exposures but, considerable damage for long-term exposures can occur. The Nomex jacket was quite damaged with damage also occurring to the inner core. Sample 2, which had Teflon extruded over the core, showed no short term damage. The long-term exposure showed some damage to the Nomex jacket, but no damage at all to the Teflon or metal coated Kevlar core. This shows that Teflon is perhaps the best polymeric insulating material.

Damping studies were also performed on Kevlar tethers. The basic Kevlar tether and Kevlar/Cu-Ni composite were the test specimens. A series of excitations were induced to the tethers while they were under static tensions. Test results showed that the Kevlar/Cu-Ni composite has higher damping and is slightly stiffer than the basic Kevlar tether.

Another area of material investigation was the drive belt. There has been no research in this area, but a drive belt has been conceptually conceived. Italian engineer Turci, of Aeritalia, has proposed a Neoprene belt covered by nylon, internally reinforced with metallic cables.[37] This idea was expanded on. Through extensive research and by contacting various companies concerning belts and materials, a drive belt was developed that is believed to be the optimal choice. This belt design is discussed in Chapter 39.

## Chapter 39. CAPTURE AND DRIVE MECHANISM - PHASE II OPTIMAL SOLUTION

In this chapter the optimal solutions for the following categories will be presented.

1. Hook / Unhook Mechanism
2. Drive Mechanism
3. Braking Mechanism
4. Materials

### 39.1 Hook / Unhook Mechanism

According to the Solution Matrix 3.6, the Rotating Disk was determined as the best method for hook / unhook operations. The Rotating Disk Mechanism was conceived by the Phase II design group.

The Rotating Disk mechanism is basically a flat disk that rotates about a fixed axis. This axis of rotation will be considered the center of the elevator. A detailed drawing of the mechanism is given in Figure 3.46. When the tether is located in the center of the mechanism (fixed axis) the center disk will rotate 90 degrees causing the tether to be captured within the mechanism. The tether can be easily removed by simply reversing the rotation of the center disk allowing the capture tether to be released. The Rotating Disk will include the following components:

- \* Drive Motor
- \* One Drive Gear
- \* Three Idle Gears
- \* Rotating Center Gear
- \* Rollers

The drive motor will be powered by a 1 kilowatt power source which will be supplied by batteries. This motor will be attached to the drive gear located at the lower right hand corner of the mechanism. A totally enclosed, nonventilated, DC permanent-magnet motor will be used in the rotating disk mechanism. A specially designed insulation for the environmental conditions of low Earth orbit, externally replaceable brushes and all-position face and base mounting, was considered in the design. Also, the motor must have reversible rotation. A drawing of the motor is given in Figure 3.47.

The Drive Gear and Idle Gears are of the same design except the Drive Gear will be attached to the motor. The design of the gears required that the center disk be able to rotate about the fixed axis and still allow the tether to enter the mechanism. The gears will allow the center disk to

## ROTATING LOCK HOOK / UNHOOK MECHANISM (OPTIMIZED SUBSYSTEM)

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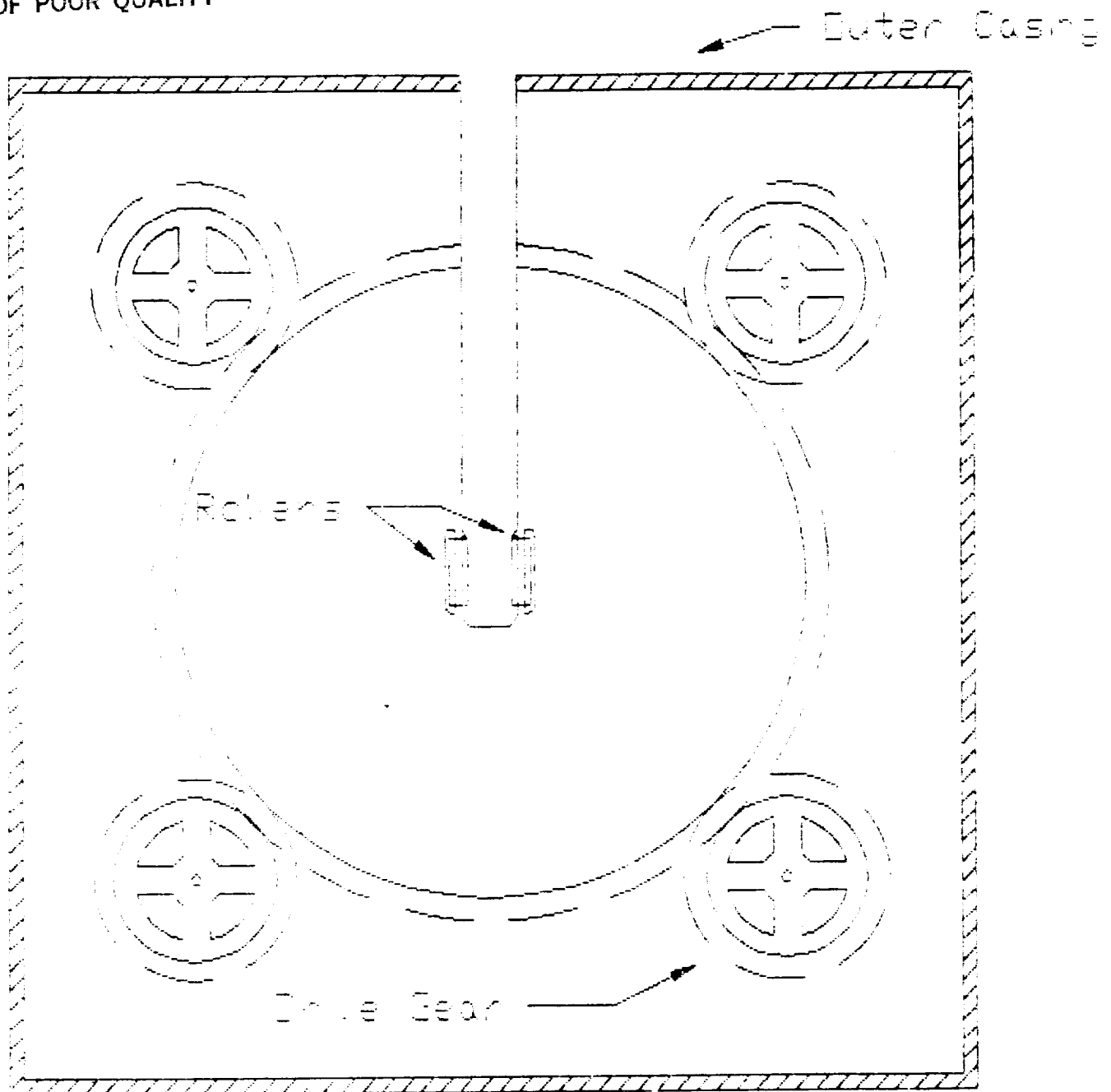


Figure 3.46

## ROTATING LOCK MOTOR

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Dayton Motor

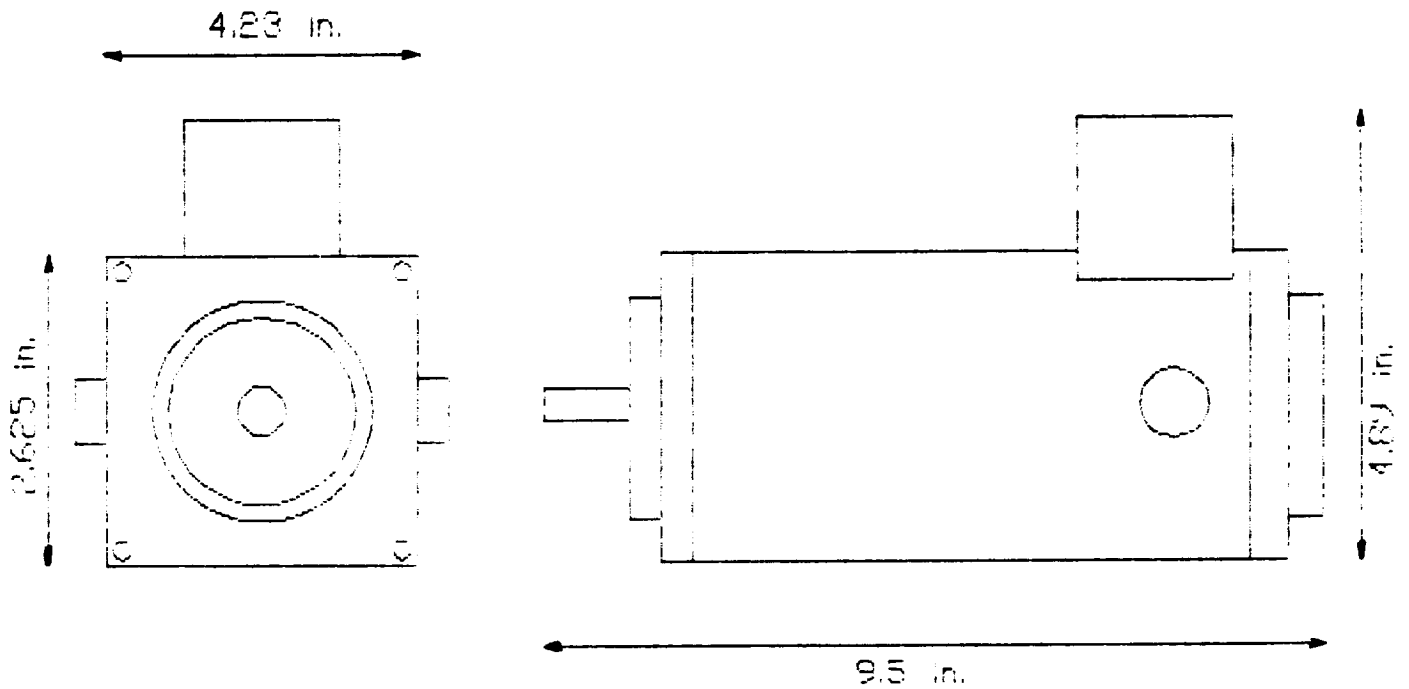


Figure 3.47

float, or ride, on the teeth of gears. A drawing of the gear is given in Figure 3.48. The gear is actually composed of three separate gears. All three gears will drive the center disk, but the outer disk will keep the center disk in place while the center disk is rotated about the tether.

#### Dimensions of Drive Gear:

Outer gear diameter	4.0 in.
Inner gear diameter	3.5 in.
Thickness in drive gear	1 in.

The center disk is similar in design to the drive gear except for a few obvious changes. The center disk will be composed of three gears which must be able to mate with the drive and idle gears. A drawing of the gear is given in Figure 3.49. The spacing between the teeth of the center disk and drive gear must allow the tether to pass within the channel created by the center disk. The outer gear will be driven by the drive gear while the inner gear will keep the center disk in place during center disk rotation. A picture of the mating of the gears is given in Figure 3.50.

#### Dimensions of Center Disk:

Outer gear diameter	10.0 in.
Inner gear diameter	9.5 in.
Thickness of center disk	1.0 in.

The center disk will have rollers attached to both sides of the channel created by the disk. These rollers will insure that the tether is not damaged by the sides of the channel during the operation of the elevator.

### 39.2 Drive Mechanism

According to the Solution Matrix 3.7, the dual drive with regenerative power capabilities was determined to be the optimal design by use of a decision matrix. This configuration had several advantages and one disadvantage over the other drive considerations. As indicated in the drive configuration matrix the dual drive with regenerative power excelled in the following areas:

- \* Safety
- \* Efficiency
- \* Redundancy

The only apparent disadvantage seems to be the additional cost due to the addition of the regenerative motors.

## ROTATING LOCK DRIVE GEAR

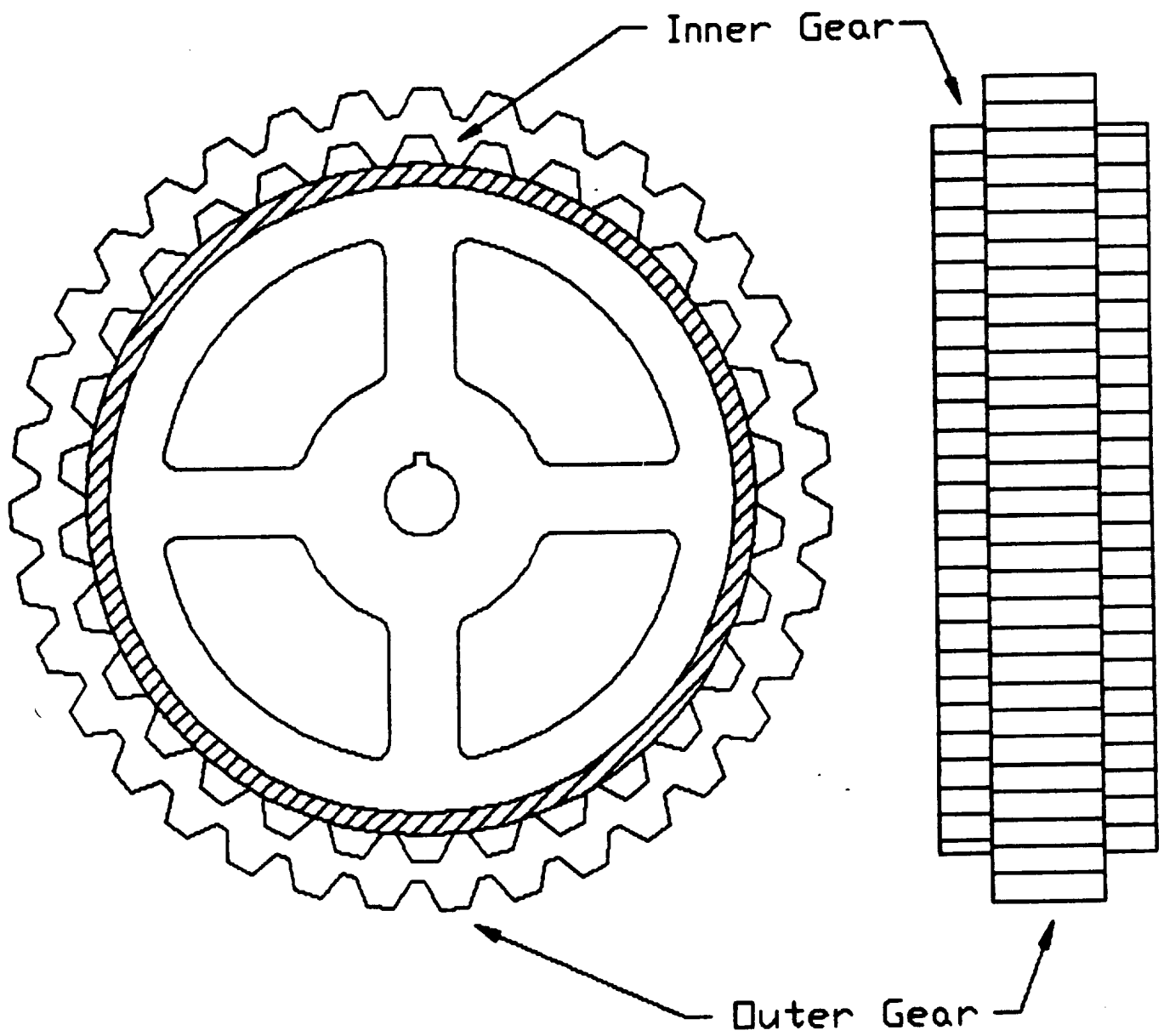


Figure 3.48

## CENTER DISK

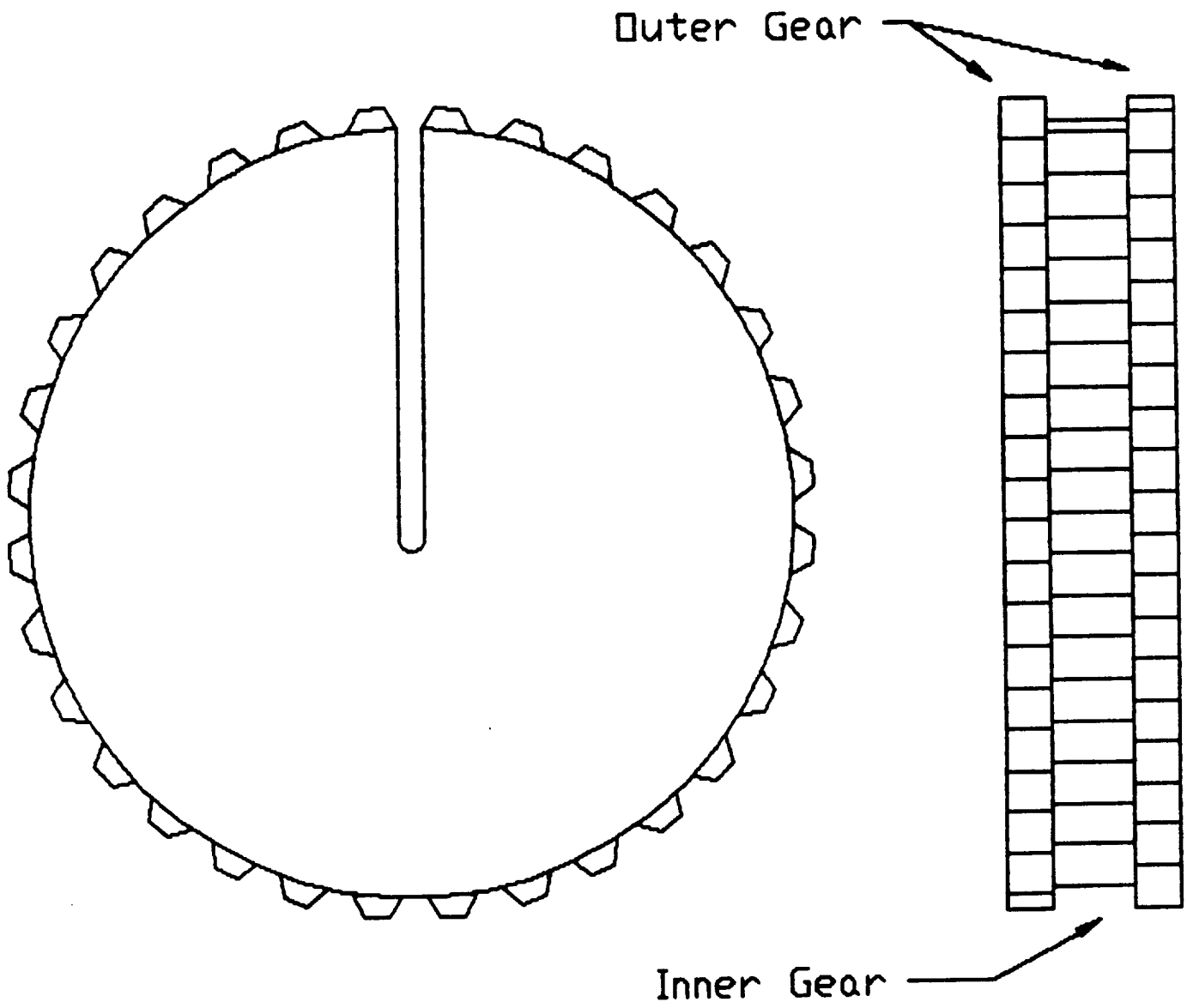


Figure 3.49



## MATING OF DRIVE GEARS

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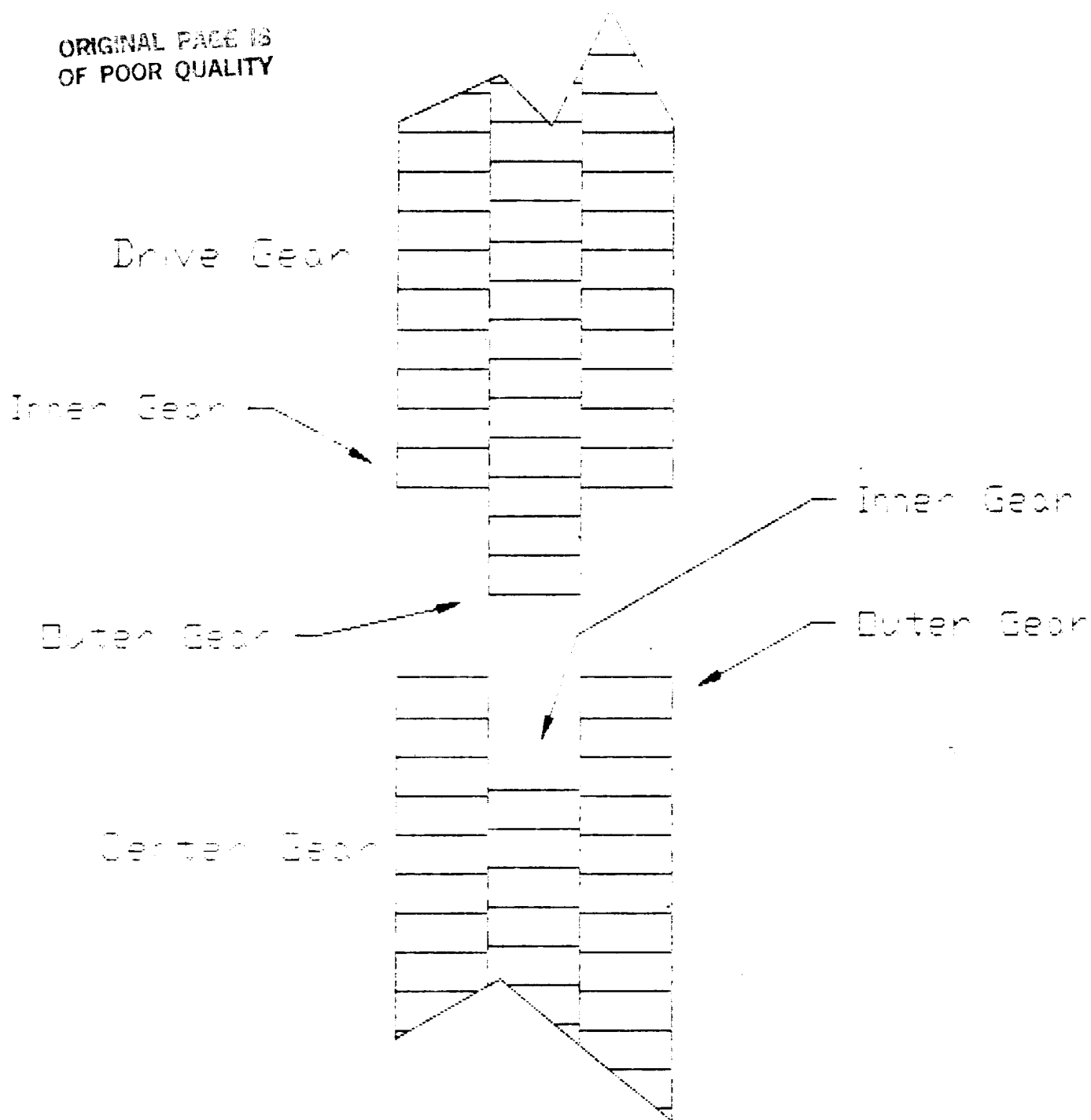


Figure 3.50

Figure 3.51 is an illustration of the overall optimal design. As seen in the figure the system consists of two drive units, one placed at the top and bottom of the elevator. Figure 3.52 is a detail of one of the drive units that makeup the overall drive system. Each of these drive units consists of the following:

- \* Two drive motors
- \* Two regenerative motors
- \* Four drive pulleys
- \* Three linear actuators
- \* Two tensioning pulleys
- \* Two toothed drive belts
- \* One pressure block

These components have been discussed in the Phase I optimal solution section except the regenerative motors and the tension pulleys which will be discussed in the following sections.

#### 39.2.1 Regenerative Motors

Four D.C. shunt-wound motors will be used as regenerative motors. When the elevator is traversing the tether these freewheeling motors will act as generators which will produce a voltage. These same motors can be used as backup drive motors by simply applying a voltage to them.

#### 39.2.2 Tensioning Pulleys

Because of the elasticity of the drive belt material it is necessary to incorporate tensioning pulleys to remove the excess slack.

The linear actuators discussed earlier will be used to apply constant pressure to the drive belt. The 2 inch diameter tensioning pulleys are crowned to a height of 1%-3% of the face width to help keep the belt in alignment (see Figure 3.53).[47]

#### 39.3 Braking Mechanism

The optimal solution to the problem of braking the LEOTAD was found to be the extended rotor configuration (ER). This configuration incorporates several advantages over the other designs presented. As the braking mechanism solution matrix indicates (Matrix 3.9), the extended rotor disc brake in the areas of safety, controllability, and efficiency. While this configuration achieved only moderate scores in life span, EVA requirements, and maintainability the other configurations, at best, only matched the ER's optimization matrix scores.

# LOCATION OF DRIVE AND LOCK UNITS

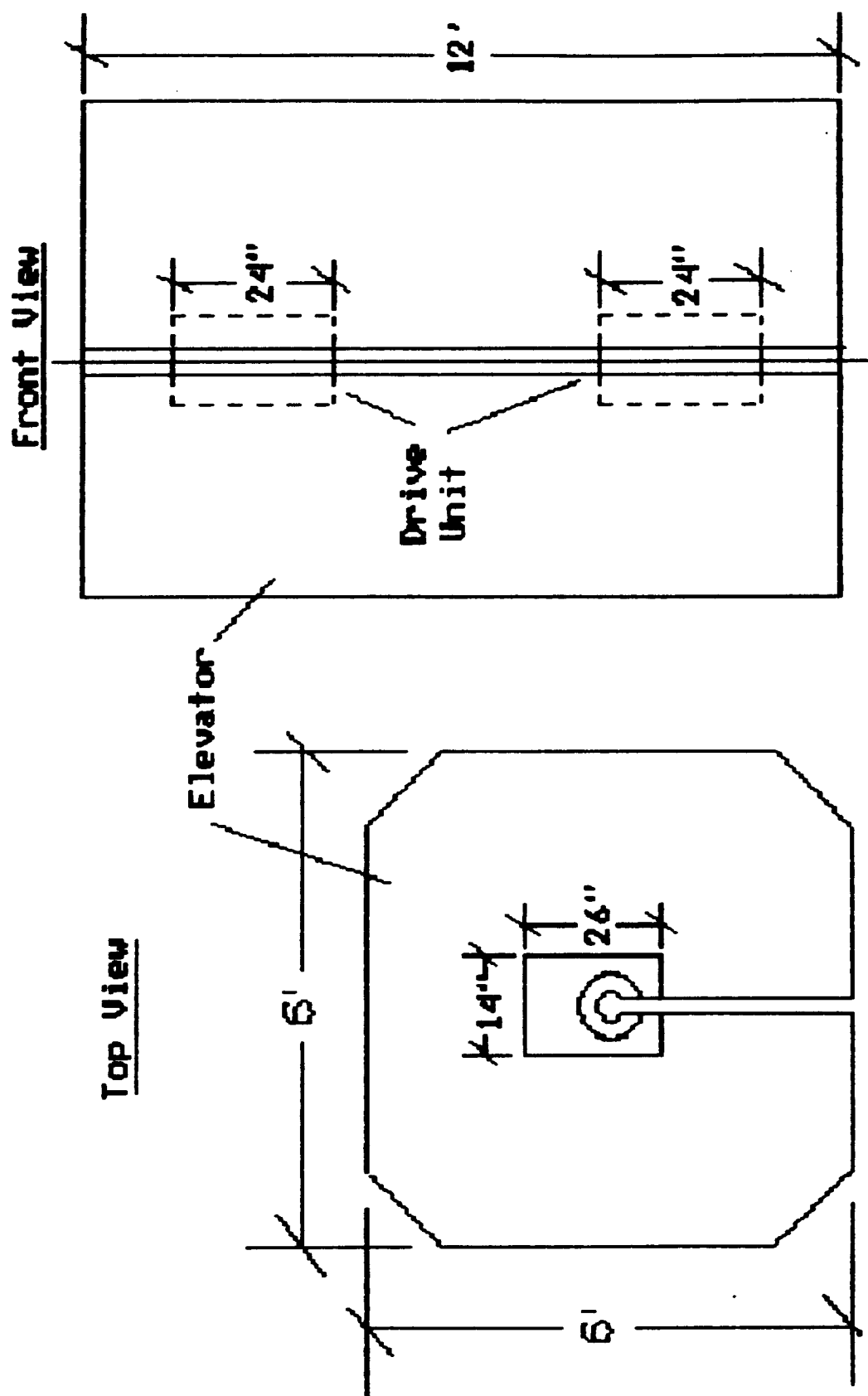


Figure 3.51

# *BI-WHEEL FRICTION BELT W/ REGENERATIVE MOTORS*

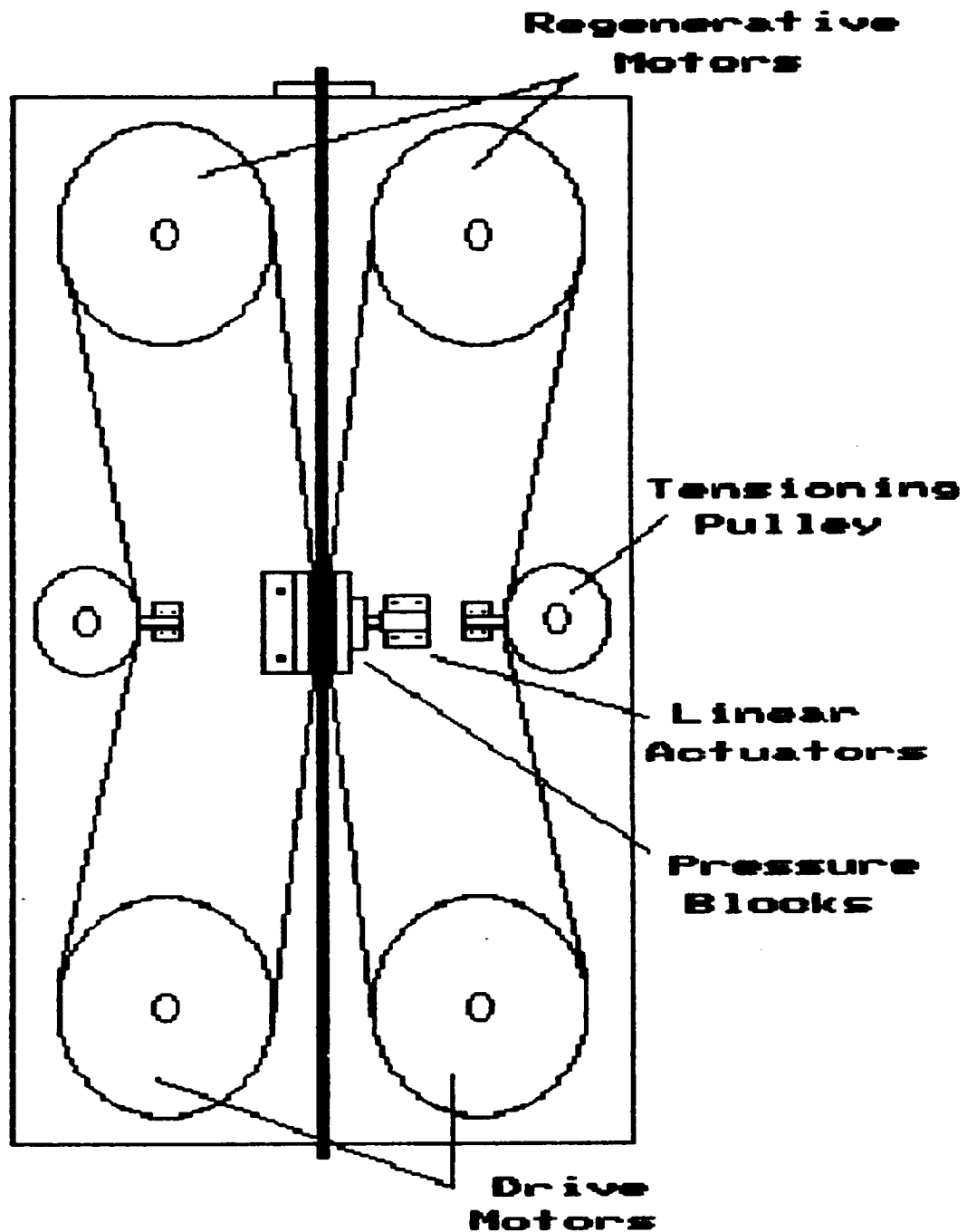


Figure 3.52

## TENSIONING PULLEYS

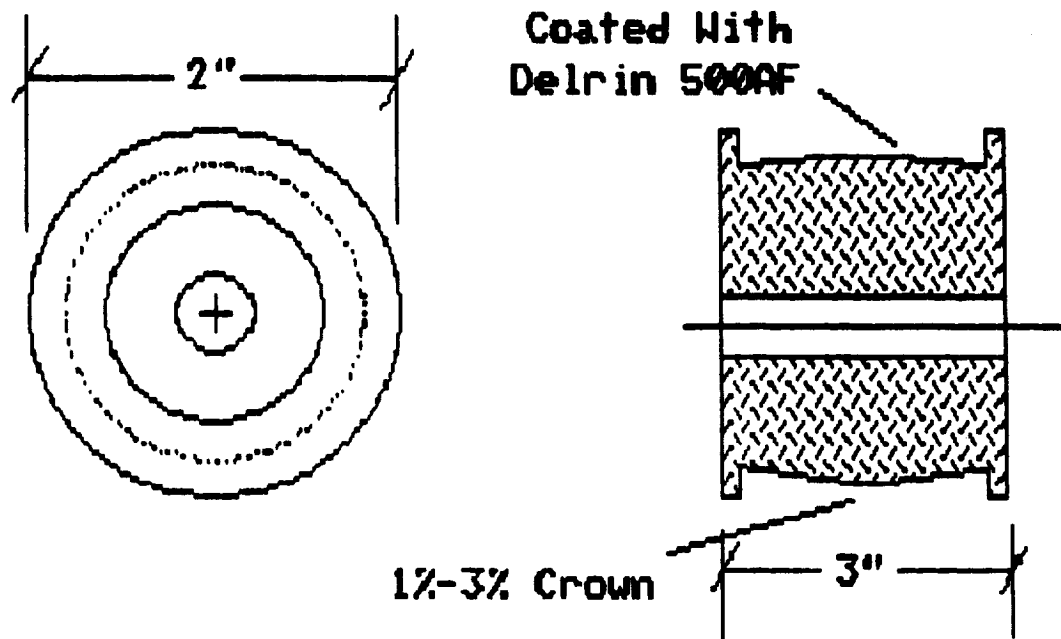


Figure 3.53

#### 39.4 Materials

During Phase II of FMI's contract with NASA, three sample tethers were constructed. From the test data recorded earlier it is obvious that Sample 2 is the optimal tether at this point. Sample 2 revealed superior data in all of the tests that were performed on the specimens. It showed a lower electrical resistance than Samples 1 and 3. This would allow for more current to flow through the tether with lower power loss. Sample 2 also showed a larger breakload value than Samples 1 or 3. In the final tests oxidative properties were compared. Due to the Teflon coating of the core on Sample 2, mass loss was less in both short-term and long-term exposures in the oxygen plasma chamber. Much research and testing still needs to be performed in the area of space tethers, but for now, Sample 2 of FMI's experiments looks promising.

Now that the tether has been optimized, a discussion of the drive belt will be presented. Expanding on Turci's idea, a belt has been developed by the members of this design phase that should withstand the load it must carry. There are several similarities between the design of this drive belt and the belts of top fuel dragsters. The notches on the belts that interface with the grooves in the sprockets are of the same concept as that presented in this report. This notch / groove interface will not allow for slip to occur between the belt and sprocket. After obtaining and reviewing literature from Pacific Belting Industries, Incorporated it has been concluded that Gate's Poly Chain GT Belts would provide the strength needed.

The belt is constructed of a high-grade polyurethane that is internally reinforced with DuPont's Kevlar fiber to provide a high tensile strength.[48] Special ribs on the belt top help increase flexibility. These ribs may also help grip the tether while LEOTAD is in motion. Other special properties of the Poly Chain Belts include a temperature range of -65F to +185F (-54C to +85C), corrosion resistance, abrasion resistance, no lubrication needed, and little retensioning required.[48] The dimensions of each drive belt shall be 47 inches long and 2.67 inches in width. (Figure 3.54)

The top and bottom of the belt will have a type of DuPont's Delrin acetal resin on the outer one-third of the surfaces. (Figure 3.55) The kind of Delrin this group recommends is Delrin 500 AF, which has extremely low friction and wear when in contact with itself.[49] Delrin 500 AF also has a melting temperature of 347F (175C). The only drawback is that Delrin is very sensitive to ultraviolet and gamma radiation.[49] With proper shielding and environmental control, Delrin will retain its self-lubricating property.

## TOOTHED DRIVE BELT

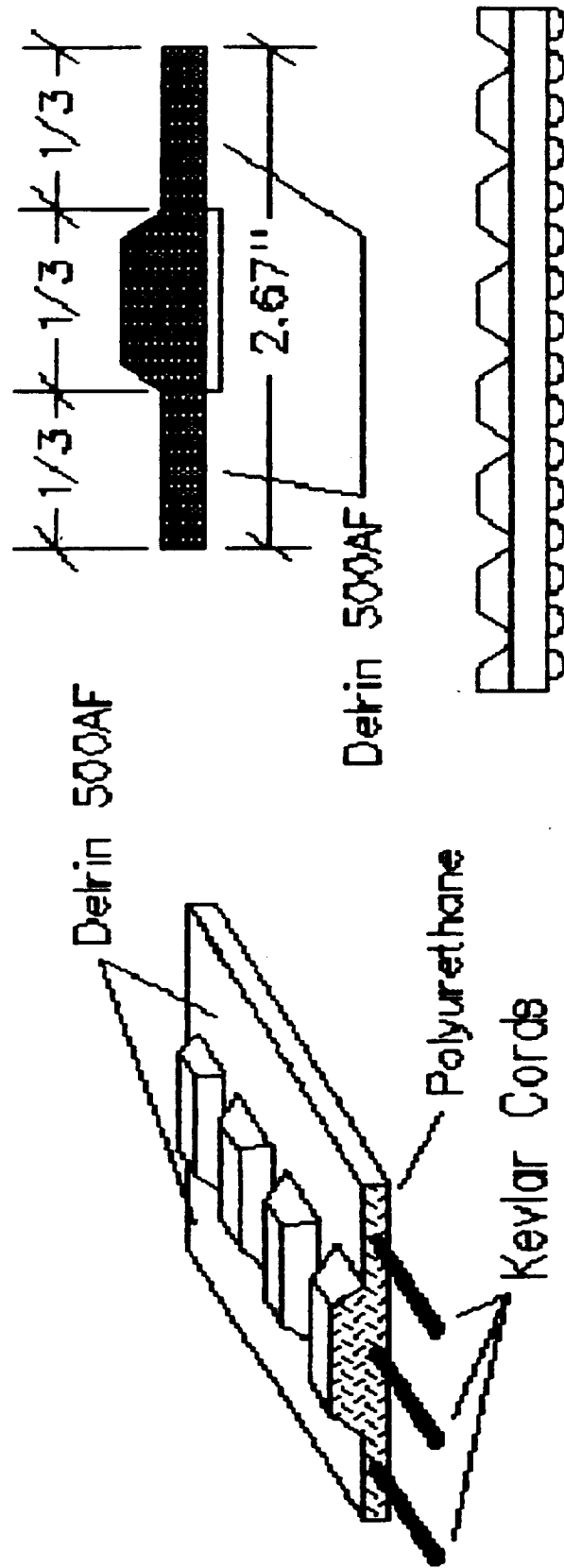


Figure 3.54

Delrin 500 AF will also be used on the surface of the sliding block which is attached to a linear actuator that applies pressure to the belt which in turn grabs the tether to initiate motion. The surface of the tension pulley will also be covered with Delrin 500 AF to reduce friction. The tension pulley will keep the drive belt tight when the linear actuator is disengaged. The combination of all these components and materials operating in unison should prove to be efficient.



## SECTION IV.

### POWER GENERATION AND TRANSMISSION SYSTEM

#### DESIGN PHASE I.

- \* Electrodynamic Tether
- \* Solar Power
- \* Radioisotopic Power
- \* Storage Strategies

#### DESIGN PHASE II.

- \* Electrodynamic Tether
- \* Photovoltaics
- \* Microwave Systems
- \* Fuel Cells
- \* Storage/Backup Strategies
- \* Power Transmission
- \* Component Configuration

## SECTION IV. POWER GENERATION AND TRANSMISSION SYSTEM

### INTRODUCTION

The operation of the TES will provide many attractive functions in LEO, however, without an independent power supply it will be no more than a drain on overall SS operations. Since the SS power supply will be allocated to each nation's individual requirements, the elevator must have totally self-sufficient power generation and transmission capabilities. The TES needs a clean, safe, reliable source of power to perform its many functions so that it does not affect the sensitive experiments taking place. The total design power requirement was estimated at 3.5 kW in Phase I. It must supply power for the capture and drive mechanism, the robotic arms, and any logistics support. After further detailed calculations, the maximum electrical output needed was determined to be 10 kW in Phase II.

The power generation and transmission system has to meet many specifications. The system must be safe. It cannot cause any adverse effects to the SS structure, personnel or any experiments. It must be reliable. Down time over the thirty year life expectancy of the SS must be kept to a minimum and should be maintained with a minimum of extravehicular activity (EVA). Also of concern in the design is to keep the size and weight to a minimum. This is done for two reasons. The first is to maximize the cargo space available on the TES. The second is to keep the affects on the TES's movement minimal (i.e. accession, recession and robotic arm movement must not be hindered). Other important governing restrictions are technological feasibility and reliability.

The contents of this section describe the various alternatives to fulfill the power generation and transmission needs of the TES. Because of the need for an independent power source aboard the TES, the overall objective of Design Phase I is to discover general forms of power production methods which could be used on the SS tethered elevator. Design Phase II concentrates on a more in-depth analysis of the methods of power production, transmission and storage/backup. Phase II also coordinates the system implementation with the other components of the elevator.

#### SECTION IV. POWER GENERATION AND TRANSMISSION SYSTEM DESIGN PHASE I

The following preliminary power generation systems were studied for their feasibility aboard the tethered elevator:

1. Electrodynamic Tether
2. Solar Power
3. Radioisotopes
4. Storage Strategies

#### Chapter 40. ELECTRODYNAMIC TETHER POWER SYSTEM

The basic electrodynamic tether system which will be tested on upcoming Shuttle flights (See Figure 4.1), is composed of two main components, the electrodynamic tether, and two cathodic contactor assemblies at either end. Systems of this type are designed to convert mechanical energy into electrical energy by the movement of a conducting wire through the Earth's magnetic field and ionospheric plasma, at the expense of the system's orbital energy.[50] The upcoming mission is designed to verify the existence of an electromotive force (emf) across the length of the tether proportional to the velocity of the system, the magnetic field strength, and the tether length. Furthermore, NASA hopes to prove that a current can be made to flow through the tether and that the plasma contactors will facilitate the closure of the circuit through the ionosphere. Next, research indicates that up to 200 volts per kilometer of tether in low orbit can be achieved, with a net power to payload of 400 watts per kilometer.[52] Finally, the current driven through the tether is expected to be between seven and ten amperes. This data will be tested as well on the upcoming Shuttle missions.

The emf acts to create a potential difference across the tether by making the upper end of the tether positive with respect to the lower end. [51] Current is produced by an electrical contact with the Earth's plasma environment. Contact is provided by plasma contactors to establish a current loop through the tether, ionosphere and external plasma.

The ionosphere's ability to sustain a current is optimized by keeping the tether current density lower than that of the ionosphere. The plasma contactors spread the current density along the length of the tether, allowing collisions with neutral particles, thus enabling electron migration across the field lines and completion of the electrical circuit.[51]

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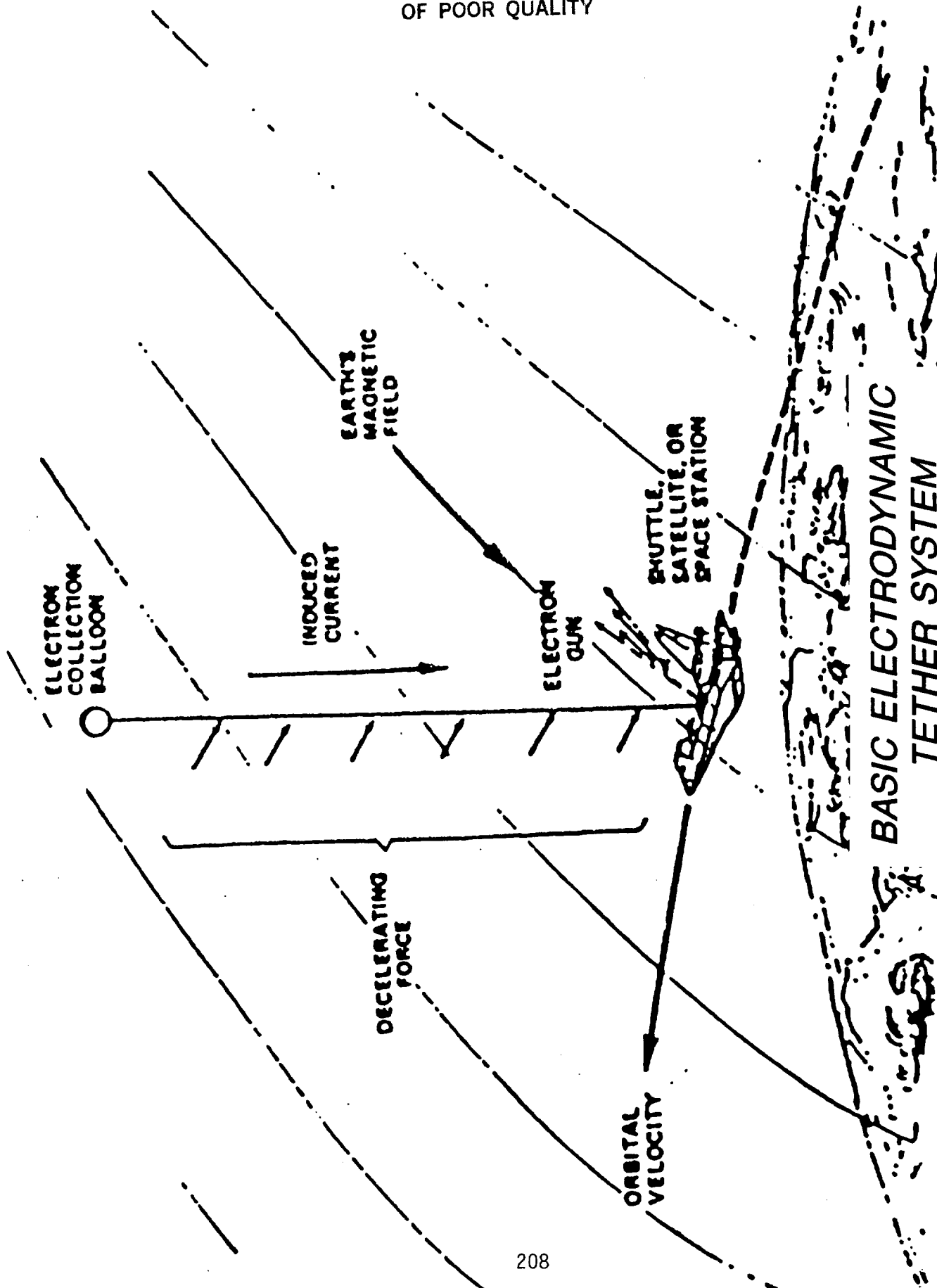


Figure 4.1

For this design three different contactor configurations were considered. They are: (1) a passive large-area conductor at both tether ends; (2) a passive large-area conductor at the upper end and an electron gun at the lower end; and, (3) a plasma-generating hollow cathode at both ends. Each of these configurations has its advantages and disadvantages. The third configuration, (See Figure 4.2), was chosen for use due to its ability to automatically switch current direction, high efficiency, low power requirement with respect to the electron gun, and finally, its high range of current flow.

The tether to be used must be a high strength cable consisting of insulation to protect the conductor against current leakage, radiation and micrometeorite bombardment. The tether selected for use on the LEOTAD, (Figure 4.3), will be an aluminum wire coated with Teflon. Aluminum was chosen on the basis of its high conductivity per unit mass. Teflon contributes high resistance to oxygen corrosion.[53]

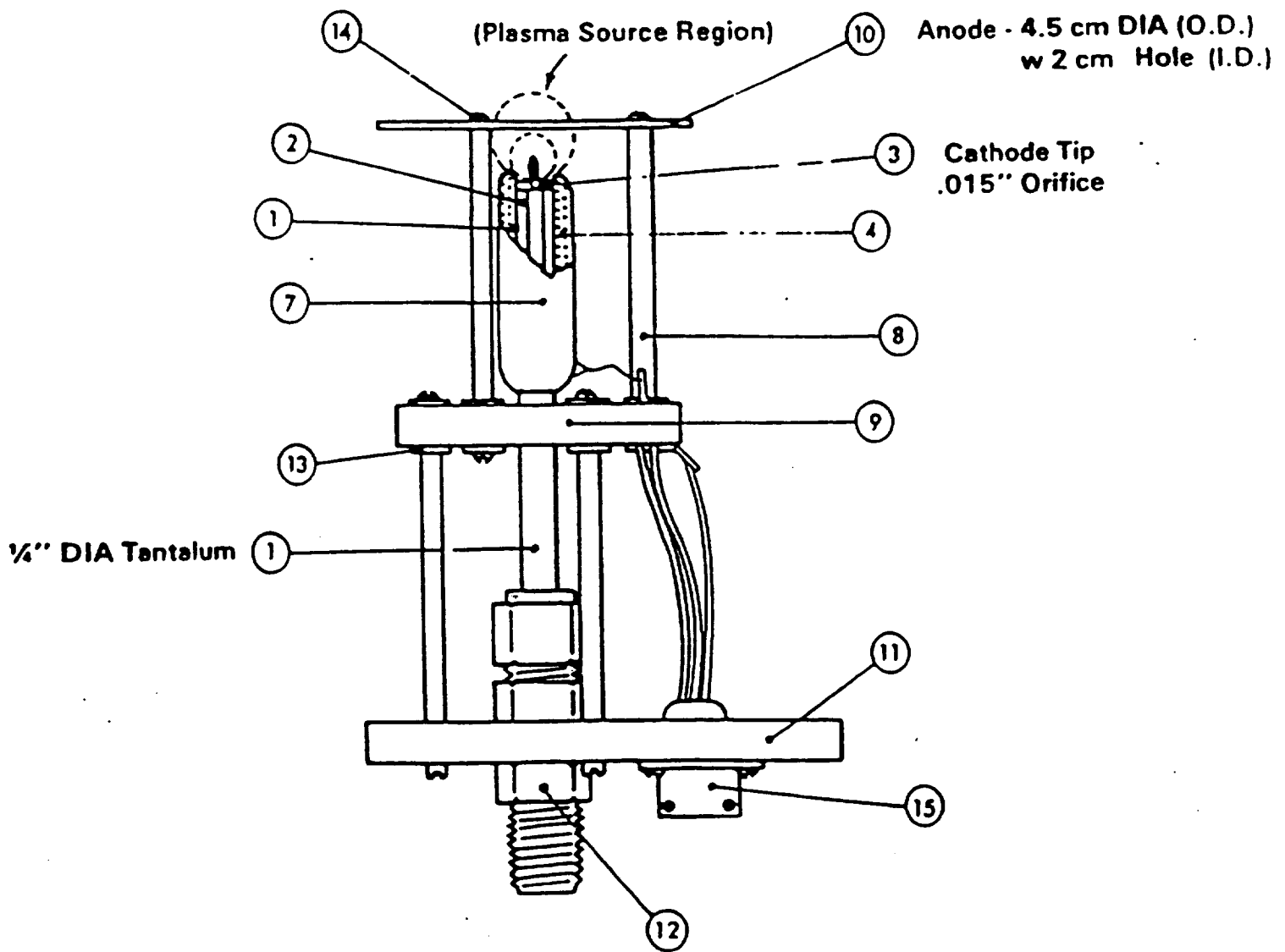
Now that the basic components for this system have been established, the problem exists as how to implement them on the LEOTAD. One design considered features three contactors placed at either end of the tether and the remaining contactor placed on the elevator itself. Uncertainty as to how the voltage across the tether might affect any controlled experiments on the elevator, as well as the uncertainty of the presence of the elevator on the current through the tether caused this design to be unfavorable.

If, however, four cathodic contactors are used instead of the three initially considered, (See Figure 4.4), the one large circuit loop could then be divided into two smaller circuits. Depending on which direction the elevator is moving along the tether, the two contactors which are not necessary, i.e. the two contactors which close the second circuit, may be turned off.

Since the effective length of the circuit will vary as the elevator traverses the tether, the voltage which is delivered to the tethered elevator system will vary with elevator position. Basically, this circuit acts as a potentiometer, since the voltage is proportional to the length of the tether conducting electricity.

One problem which had to be addressed considering the use of the electrodynamic tether was the determination of where the maximum power requirement exists, and if enough power can be generated at that point. Considering basic tether dynamics, (See Figure 4.5), it was determined that the maximum power requirement will occur as the elevator moves upward from the lowest point on the tether. Because the induced voltage is directly proportional to tether length, the voltage variance will not pose a problem for this system

# **PLASMA MOTOR GENERATOR / MOTOR CATHODE ASSEMBLY POWER SYSTEM**



# BREAKDOWN OF ELECTRODYNAMIC TETHER POWER SYSTEM

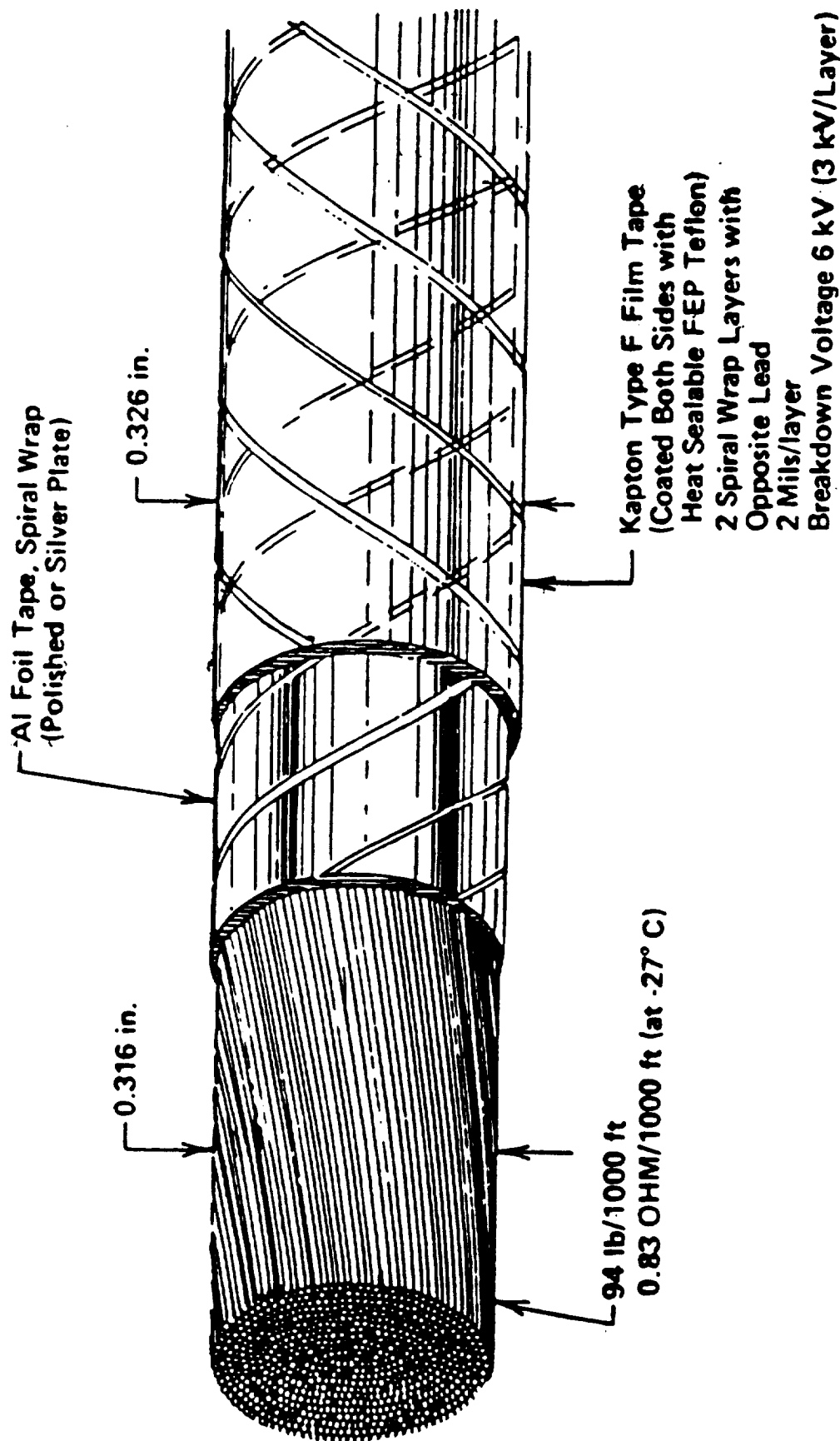


Figure 4.3

## *ELEVATOR CONFIGURATION FOR ELECTRODYNAMICS*

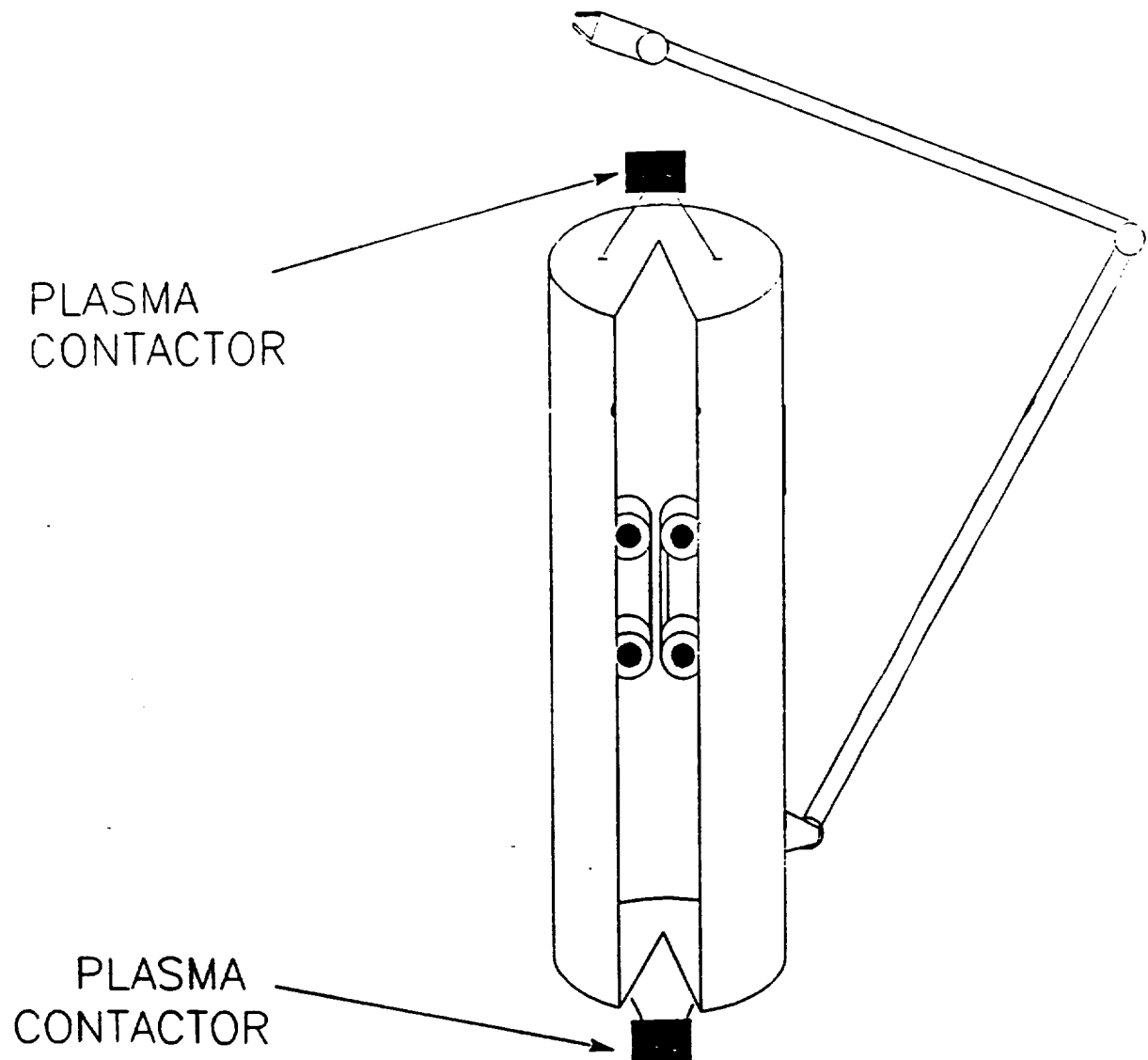


Figure 4.4



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## *BASIC TETHER DYNAMICS*

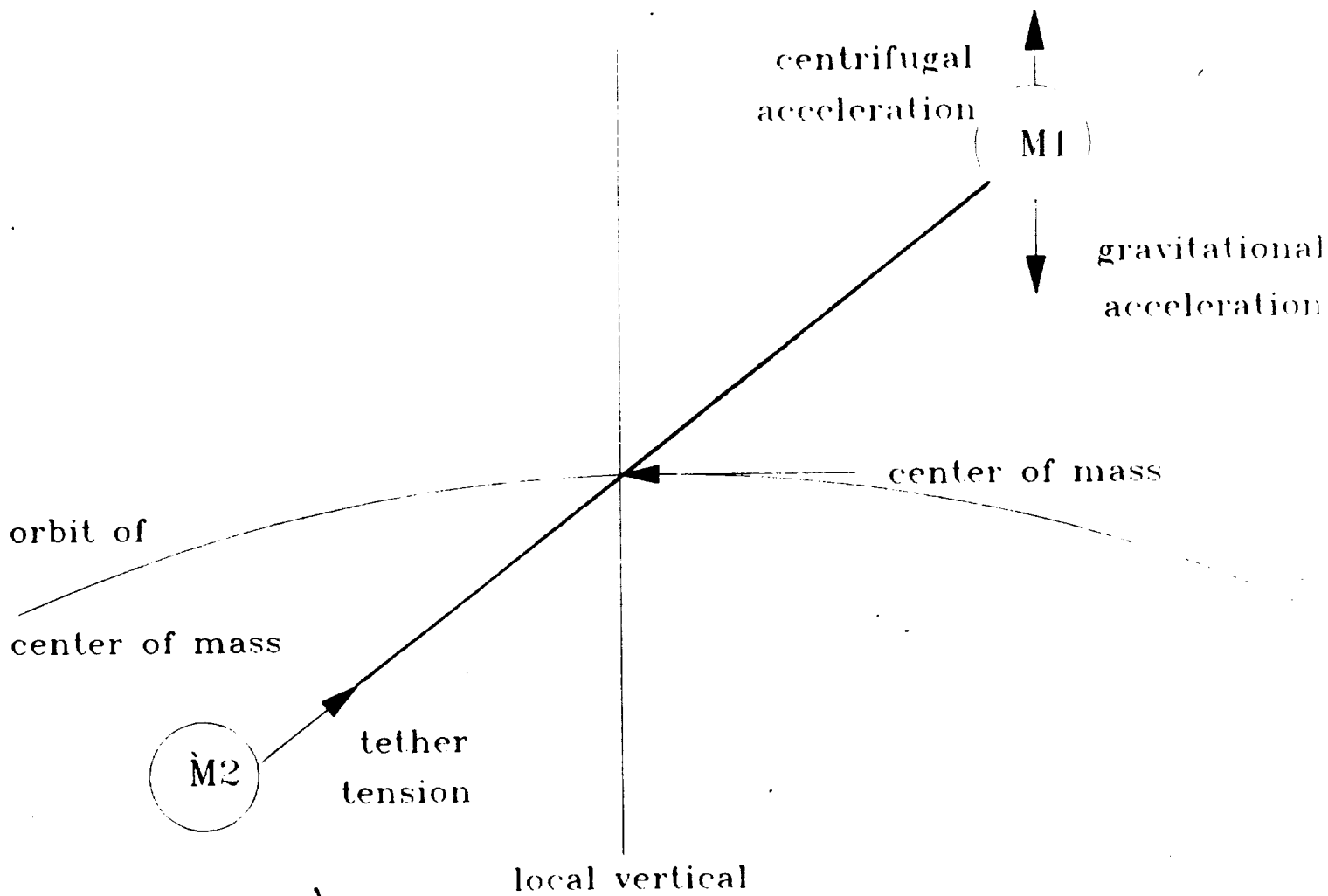


Figure 4.5

since the entire length of the tether may be utilized in that interval. When the elevator moves upward from the low point, the top circuit would be utilized and the bottom two contactors turned off to insure that the maximum tether length will be realized. Furthermore, with the use of the hollow cathodic contactors, the current can be made to flow in the desired direction.

The minimum power requirement occurs as the elevator moves from the center of mass to the lowest point on the tether. Using the bottom circuit as the driving one, the voltage will decrease to a minimum between the center of mass and the lowest end mass, thus decreasing the power delivered to the drive mechanism. Perhaps this characteristic could be used to step-down the power on the way down the tether and cause automatic braking.

Because the hollow cathodic contactors offer automatic switching of tether current direction, and the maximum power generated will occur at the maximum power requirement, the use of the two circuit electrodynamic tether model can supply an adequate amount of power to the elevator at any point along the tether.

One important point to make is that the contactors themselves, whether they be electron guns or hollow cathodes, require a certain amount of power to operate. The most significant reason for the choice of the hollow cathode plasma motor generator model was due to its very low power requirement for the automatic switching of current direction. The power requirement for such a function on the hollow cathode is approximately 10 W, as opposed to approximately 1 kW for the same function with an electron gun.[51] Of course the batteries which will be used can supply the necessary power to these devices.

The advantages the electrodynamic tether power generation system offers are constant availability of power, simplicity of design, minimal elevator surface area requirement, and no interference with the telerobotic arm. On the other hand, there are some disadvantages which must be addressed. For one, the plasma contactors need development. Results of recent plasma contactor flight tests are not yet available. Next, there is no proven space design or model; however, certain assumptions must be made concerning technological advancement. After all, the Space Station itself will not be operable in this decade, and it may be several years before the LEOTAD will be in use. Finally, the electric/electronic interface components between the plasma contactors and the user load must be defined before any definitive design considerations can be made concerning transmission. Again, this is more of a component problem than it is a design problem, and it is our belief that these

components can be developed.

While this type of power generation is experimental, geomagnetic energy using the electrodynamic tether for conversion into electrical power proves to be a most promising source for generating power for the LEOTAD.

#### Chapter 41. SOLAR POWER

The idea of using the sun as a power source is an age-old concept. Throughout time man has experimented with various methods for utilizing the tremendous amount of energy the Sun has to offer. One of the more modern methods of extracting this energy involves the use of solar cell arrays. A solar cell array is an arrangement of photovoltaic cells, electrically connected into circuits, that have the appearance of rows and columns.[54] A typical solar cell measures 1 cm x 2 cm x .01 in. and is usually sliced from silicon crystal. Applications for solar power are virtually unlimited. Due to the nature of the power generation and transmission system that is to be chosen for use on the tethered space elevator, space arrays are obviously the type of solar cell that will be investigated. Solar power is particularly well suited for a space environment. Solar cells are ideal for use in space because they do not consume fuel, they do not exhaust themselves, and they have no adverse affects on the surrounding environment.

Operation of a solar cell power system in space is a proven concept. The first solar cell array that successfully operated in space was launched on March 17, 1958, on board Vanguard 1, the second U.S. Earth satellite.[54] Since 1958 many satellites and other space vehicles have used solar cells as a power source. Two of the more well known spacecraft that utilized solar power were Skylab 1 and the Tracking and Data Relay Satellite System (TDRSS) which is presently orbiting the Earth. The spacecraft Magellan also utilizes solar panels as its power source for its journey to Venus.

There are two methods for mounting solar arrays, body mounting and external mounting. Body mounted arrays utilize the surface of the space vehicle housing, while externally mounted arrays are placed on paddles or wings. Since the number of solar cells directed towards the sun dictates the amount of power which can be generated by such panels, the orientation of these solar panels is a crucial factor in any application. Power outputs of 6 to 9 W per square foot of array have been produced.[54] It is believed that an optimal value of 10 W per square foot is readily obtainable with the aid of modern technology. Given the TES's power requirement of 3.5 kW, data suggests that 350 square feet of solar arrays

will be sufficient to meet the demand. It is possible that through a more efficient array system a smaller area would be required; however, 10 W per square foot is the most realistic output ratio achievable for this particular application. Since no definite physical dimensions for the elevator have been revealed until now it is very difficult to propose any type of body mounted array. If solar arrays are chosen as the primary source for power on the elevator, it is highly probable that externally mounted arrays will be used. If the proposed Cylindrical Elevator were used, (Figure 4.6), it would have to be approximately 80 feet long with a diameter of 15 feet. This large size is necessary since only one quarter of the elevator body can be exposed to direct sunlight at any given time. Mechanical mounting of the arrays on a curved surface would be a complicated procedure and concave panels are significantly less efficient than the standard flat design. Another problem with body mounted arrays is that they take up the majority of the surface area of the elevator. This could restrict the number of experiments conducted on the elevator. Externally mounted panels, on the other hand, would allow full use of the elevator surface and could also serve as a balance mechanism for the elevator. One of the most significant advantages of external panels is that they are much easier to orient towards the sun, (Figure 4.6), regardless of the elevator's position. Unlike body mounted arrays, external arrays would not place any restrictions on the size or shape of the elevator. Solar wings could easily be adapted to either of the two optimal elevator shapes. Both the Cylindrical Elevator and the preferred Component Elevator could be designed to use externally mounted solar arrays as their primary power source.

A common procedure for transporting solar arrays from earth to space is to have each panel sectioned so it can be folded up like an accordion. Once the spacecraft is positioned in space the folded panels are extracted and locked into place.

Four solar arrays measuring 20 feet by 6 feet could produce up to 4.8 kW of power, which surpasses the elevator power requirement of 3.5 kW. The use of four panels would be advantageous by providing some redundancy to the system as well. If one of the panels failed the remaining three panels could still satisfy the power requirement.

External arrays mounted on detachable wings offer one solution to the problem of providing power to the elevator system. Two panels could be mounted on each side of the elevator and extended by mechanical arms. This method of mounting has been used in space many times before. One such example is the panels used on the TDRSS spacecraft. Furthermore, if the arms were mounted on a base that could be

## *ELEVATOR CONFIGURATION FOR SOLAR POWER*

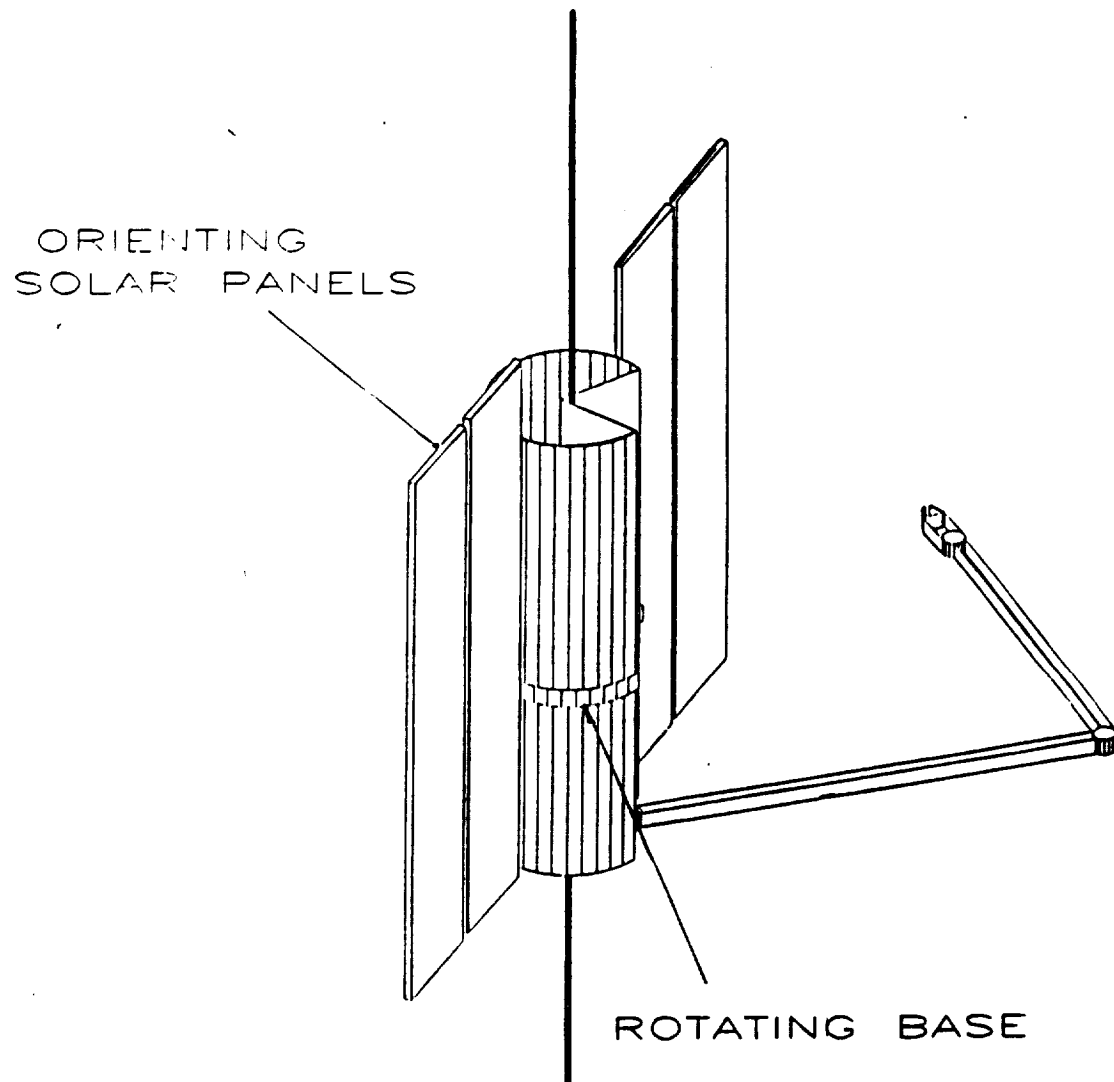


Figure 4.6

rotated around the elevator, the orientation of the panels could be greatly extended. For example, instead of having only vertical orientation, the rotation of the wings around the elevator would add lateral orientation as well. This idea could best be implemented on the proposed Cylindrical Elevator, but externally mounted arrays on the preferred Component Elevator could also be implemented.

Energy conversion processes with solar power include solar dynamic conversion, thermionic conversion, and direct photovoltaic cell conversion. Solar dynamics for use in space has been studied for the last 25 years. However, these solar dynamic conversion systems are more suitable for high power requirements such as 1 megawatt or more. Solar dynamic systems are generally large, expensive to manufacture, and the technology concerning them is still in relatively early stages. Thermionic conversion with solar arrays is a promising area presently undergoing extensive research, but since this conversion process is still experimental, it is not very feasible, considering the existing photovoltaic cell conversion process.

The most practical method of conversion is direct photovoltaic conversion of solar energy into electricity. If chosen to be used on the tethered elevator, retractable solar arrays will convert the sun's energy into electrical power and this power will be collected by interconnectors. This electrical power will be transmitted to terminals on each solar panel by use of cables, wires, and flat conductors. An electrical converter will transform the DC power generated by the arrays into the desired AC output. A regulator would aid in distributing the electricity to the storage subsystem, the robotic arm, the drive mechanism, and any necessary logistics support. Photovoltaic conversion has been preferred in the past, and given the modest power output requirement of the elevator it remains a preferred method.

The use of solar arrays is not without its problems. Transportation of the panels is more complicated since the cells must generally be compactable. As previously stated, retractable or folding arrays are available but they are not as simple in design as solid arrays. Another disadvantage is that solar cells are prone to damage from objects such as micrometeorites and photon bombardment. Therefore, shielding of solar cells is a design requirement that must be considered. The materials used for shielding must be durable, and the front shielding must be transparent so it does not decrease the solar panel's efficiency. Typical solar cell shielding can be seen in Figure 4.7. Furthermore, solar power cannot be provided 100% of the time. At low Earth orbit altitude, a complete revolution around the Earth occurs every 90 minutes. Therefore, the Sun will only release its energy on the solar arrays every 45 minutes. Obviously solar

## TYPICAL SOLAR CELL SHIELDING

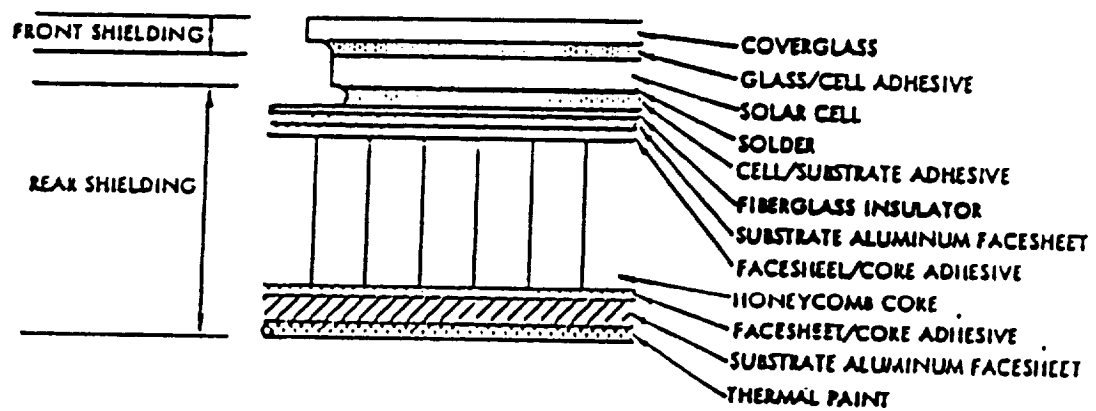


Figure 4.7

power is not obtainable when in darkness, thus a storage system is necessary. The use of Nickel Cadmium, Nickel Hydrogen, or salt batteries with solar power is a common and necessary process, and helps to alleviate this particular problem. A competent storage subsystem is always important and it is a major factor in the design of a solar power generation system. The batteries will serve a crucial role because they will be the sole source of power during equinox. Advantages of solar arrays also include a declining cost along with support from numerous systems that have been previously used.

The use of externally mounted solar arrays with direct photovoltaic conversion offer the most adequate solution to the power requirement problem of the tethered space elevator. Although it is limited by the availability of sunlight, this method of generation is a proven method and can afford the 3.5 kW requirement in conjunction with an adequate backup power source.

## Chapter 42. RADIOISOTOPIC POWER SYSTEM

Radioisotopic Power generators are an attractive means of fulfilling the LEOTAD's power requirement. They are highly compact, highly reliable and capable of producing electrical power for extended periods of time. Through appropriate selection of radioactive isotopes and energy converters, the problem of power generation in many space applications can be solved. This is the type of research which the Martin Company has applied in developing the SNAP (Systems for Nuclear Auxiliary Power) power generators which have already served as power sources to spacecraft. Space technology has benefitted through applications such as the SNAP-3B7 power generator installed on the transit-4A navigational satellite.[55]

Energy from radioisotopic decay initially appears in the form of kinetic energy from decaying particles. From here energy conversion techniques must transform the kinetic energy into voltages which can be more easily utilized. The two main types of energy converters used to address this problem are as follows.

- \* Heat engines
- \* Nuclear batteries

### 42.1 Heat Engines

With the use of heat engines the kinetic energy of the decaying particles first degrades to heat through collisions with each other. Then, using a heat engine, it transforms



the heat into voltages that can be more easily utilized. For the purposes of this paper the classification of heat engines is further divided into two subcategories:

- \* Dynamic type
- \* Direct conversion type

#### 42.1.1 Dynamic Type

A dynamic conversion system is the transfer of heat energy from the decaying radioisotopic fuel block to a working fluid. Thus the temperature of the fluid increases. This energy can then, through the use of a turbine, be transferred to a generator which produces electrical energy. This is a general description and the actual details differ depending on which thermodynamic cycle is considered.

- \* Rankine cycle
- \* Brayton cycle
- \* Stirling cycle

The Rankine cycle, (Figure 4.8a), would utilize a liquid metal working fluid which would actually cycle through vapor and liquid phases. This is referred to as a two phase working fluid. Examples of these types of working fluids include Mercury, Potassium, and Rubidium.[55] The Brayton cycle, (Figure 4.8b), uses vapor working fluids which require no phase change. Examples of these gasses are Helium, Neon, and Argon.[55] The Stirling cycle also uses a single phase gas as a working fluid, however a reciprocating engine is employed in place of a turbine.

Each system has unique advantages and disadvantages. The Rankine cycle takes advantage of the better heat transfer properties of liquid metals. On the other hand, the Brayton and Stirling cycles make use of gasses which are noncorrosive, unlike the two phase fluids of the Rankine cycle. Furthermore, there is no phase change required in the vapor cycles. Overall problems faced by dynamic heat engines in space include the lack of long demonstrated life span due to wear of mechanical parts and corrosion.

#### 42.1.2 Direct Conversion Type

The second type of heat engine is referred to as the direct conversion type because engines in this category directly convert heat energy into electricity without the need for dynamic machinery. The two types of direct

# DYNAMIC CONVERSION HEAT ENGINE CONFIGURATIONS

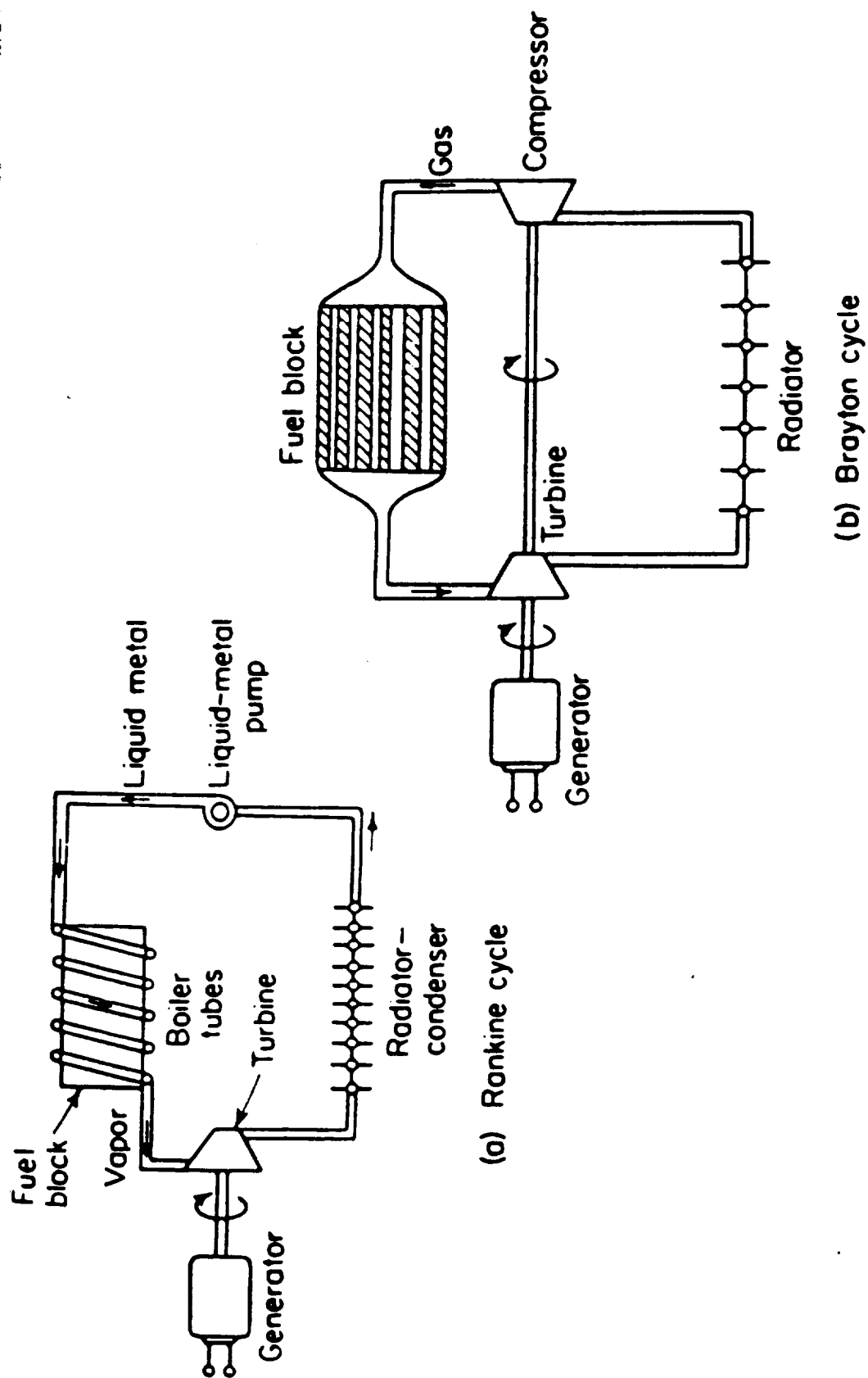


Figure 4.8

conversion heat engines which apply to our design are as follows:

- \* Thermoelectric
- \* Thermionic

Thermoelectrics is a proven technology which has been used extensively in the space program. The conversion from heat energy to electricity is made possible through the use of solid state semiconductor devices. In this conversion process, one side of the thermoelectric element is capped by a hot shoe, (approximately 1300 K)[56], which receives heat from the heat source (See Figure 4.9). Heat flows into the hot shoe and then through the thermoelectric element. The heat then flows out through a cold shoe, (approximately 573 K)[56], and into a waste heat dump. These thermoelectric elements are semiconductors and are coupled into pairs containing one p-leg and one n-leg element each. Due to the temperature difference across the elements, positive electron holes flow to the cold end of the p-leg and conduction electrons flow to the cold end of the n-leg. Thus a potential difference proportional to the temperature difference is built up. A schematic for this type of power conversion is shown in Figure 4.10. Generators operating under this principle are termed Radioisotopic Thermoelectric Generators (RTG's). The first RTG's, however, were built with the project designation "Systems for Nuclear Auxiliary Power" (SNAP).

In 1976 the Department of Defense launched two communication satellites which were powered by RTG's. These generators are still operational today after over ten years, thus proving the reliability of the system.

A further advanced RTG will be used on the Galileo spacecraft and will be designed with modular units of thermocouples. The design planned for use on Galileo consists of a cylindrical radioisotopic fuel cell, otherwise known as General Purpose Heat Source (GPHS), with single thermoelectric couples surrounding the circumference. This design is shown in Figure 4.11. Project LEOTAD will utilize modular RTG's, or Modular Isotopic Thermoelectric Generators (MITG), similar to Galileo's. However, rather than using single thermal couples around the heat source module, the modular RTG's will use multicouples fixed to each hot shoe. For each heat source module eight multicouples will surround it. Each multicouple provides approximately 2.5 watts at 3.5 volts dc; where an equivalent uncouple would provide only 0.5 watts at 0.2 volts.[56] When the modules are assembled they will form cylindrical RTG units, each measuring 42.5 inches in length and 13.5 inches in diameter. Each cylinder will house eighteen heat sources stacked one on top of the other, like batteries stacked in a flashlight. Cylinders

## COMMON HEAT SOURCE FOR RTG's

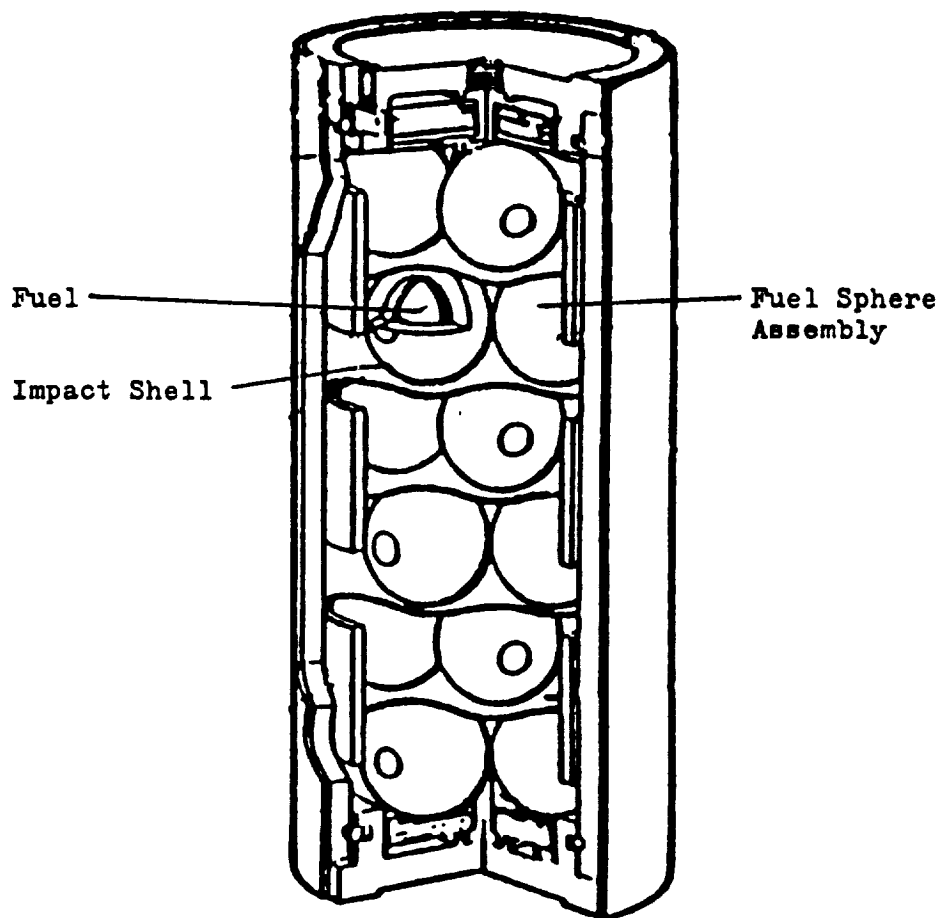


Figure 4.9

## *RADIOISOTOPIC THERMOELECTRIC GENERATOR*

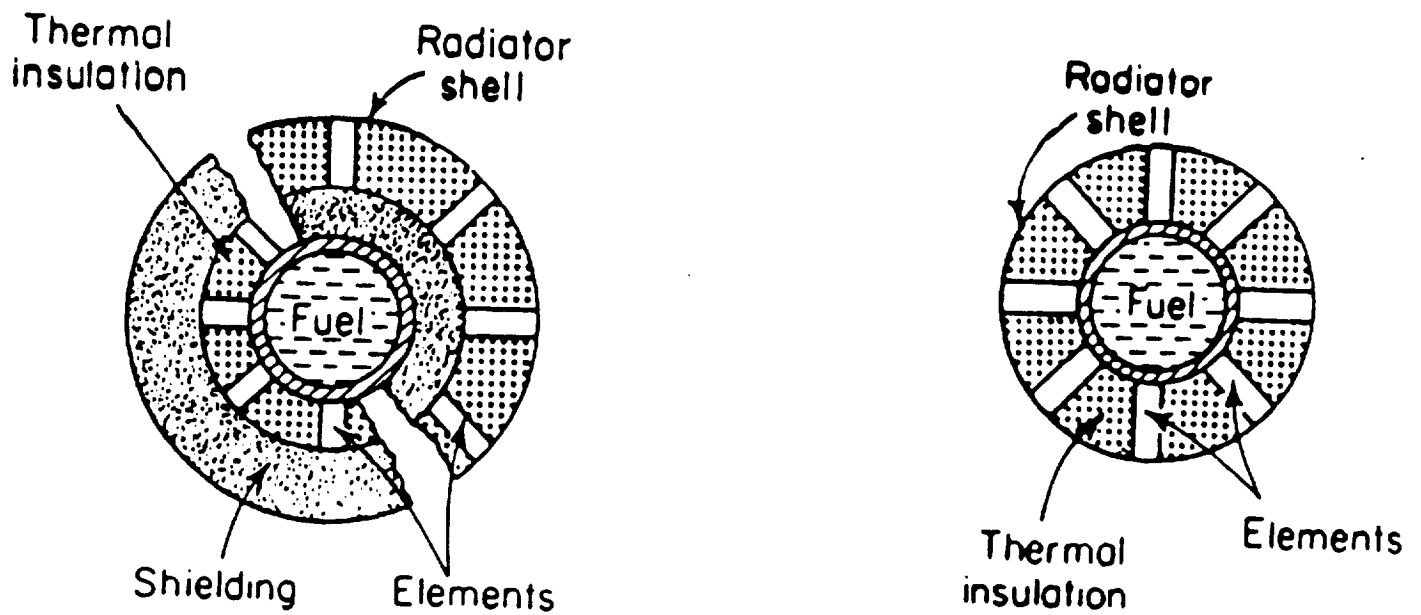


Figure 4.10

## GENERAL PURPOSE HEAT SOURCE FOR RTG's

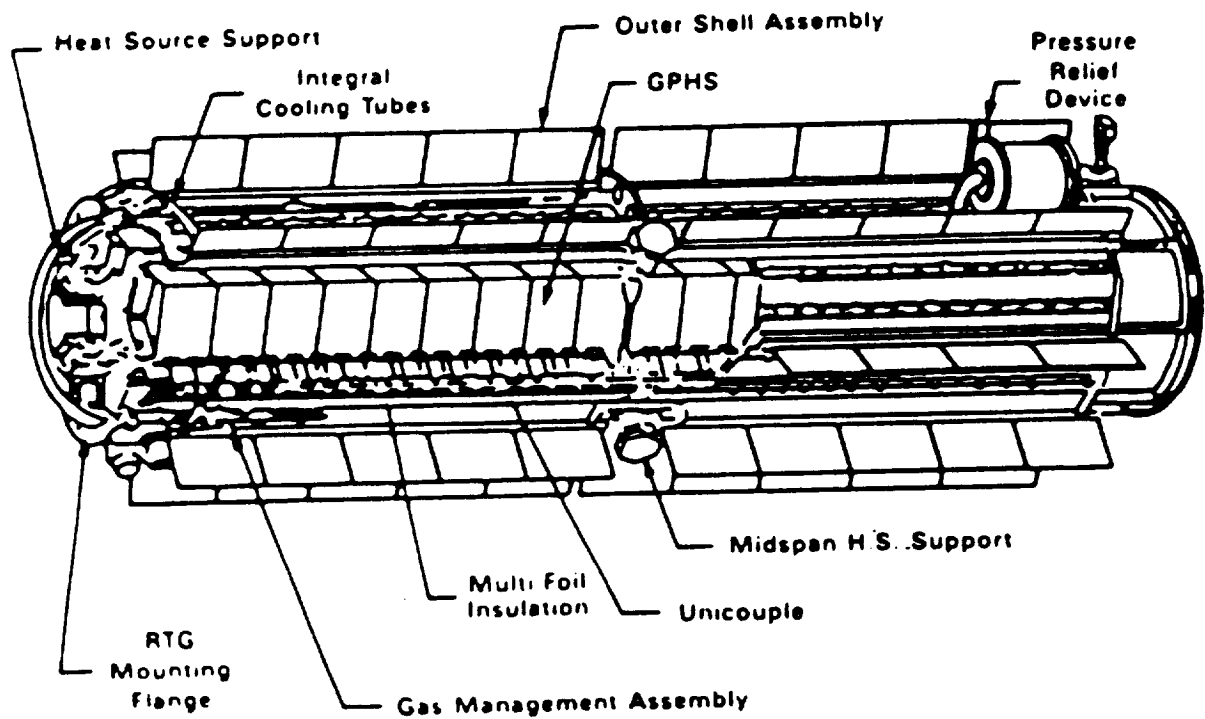


Figure 4.11

with these dimensions are capable of producing 342 watts of power.[56] This configuration of an RTG is shown in Figure 4.12. In the design for the LEOTAD, a total of eight such RTG's will be necessary to provide the 3.5 kW required.

The RTG's will be mounted external from the elevator so as not to interfere with the controlled experiments attached to the elevator. Two configurations, as shown in Figures 4.13 and 4.14, have been designed. In Figure 4.13, the RTG's will be mounted along the same plane of a short boom extended from the elevator.

In Figure 4.14, the RTG's will be mounted at a 90 degree angle from a horizontal boom extended from the Component Elevator. This configuration is advantageous in that the boom and RTG's may provide some regulation of the center of mass. The power will be transmitted via terminals located on each of the multicouples surrounding the heat source modules. The battery supply will be located in the housing of the elevator and connected to the RTG's by connection cables, thus satisfying the redundancy requirement. The power-to-weight ratio for the MITG system should be 7.7 watts/kg.[57]

The thermoelectric material that will be used in the multicouples will be Silicon-germanium. Although the efficiency of thermocouples made from this material is relatively low (less than 10%),[57] they are able to withstand the high temperatures of the GPHS. This characteristic of the material contributes to its high reliability and longevity.

As the plutonium-238 decays there is a drop in the amount of heat produced. This drop is of the order of one percent of total power loss from the RTG a year. This loss can either be accepted or can be accounted for by increasing the power produced at the start of the mission to slightly above total power requirements. When the beginning power output is increased the power output will remain at or above the requirement for a longer time.

While thermoelectrics has been researched extensively for space applications, research and development in thermionics has just recently been renewed since coming to a virtual halt in the early 1970's.[56] Thermionic energy conversion directly transforms heat into electricity through means of thermal electron emission phenomena. The thermionic converter consists of two surfaces separated by a small gap. (See Figure 4.15) One surface is supplied heat from the radioisotopic fuel cell and emits electrons, while the other surface, which is kept cooler, collects electrons. Thus a potential difference is created. The radioisotopic fuel cell supplies enough heat to the emitter to maintain a temperature

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## MODULAR RTG WITH THERMOELECTRIC MULTICOUPLE

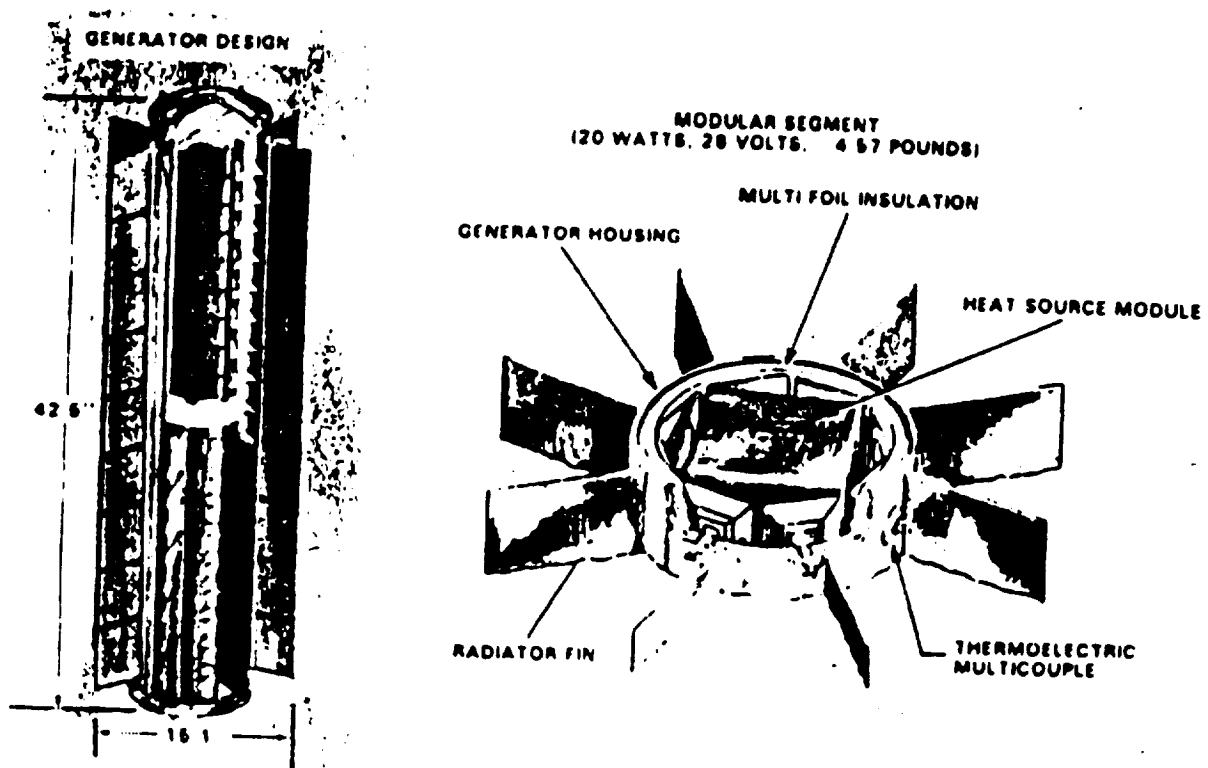


Figure 4.12



## *ELEVATOR CONFIGURATION USING RTG POWER SOURCE*

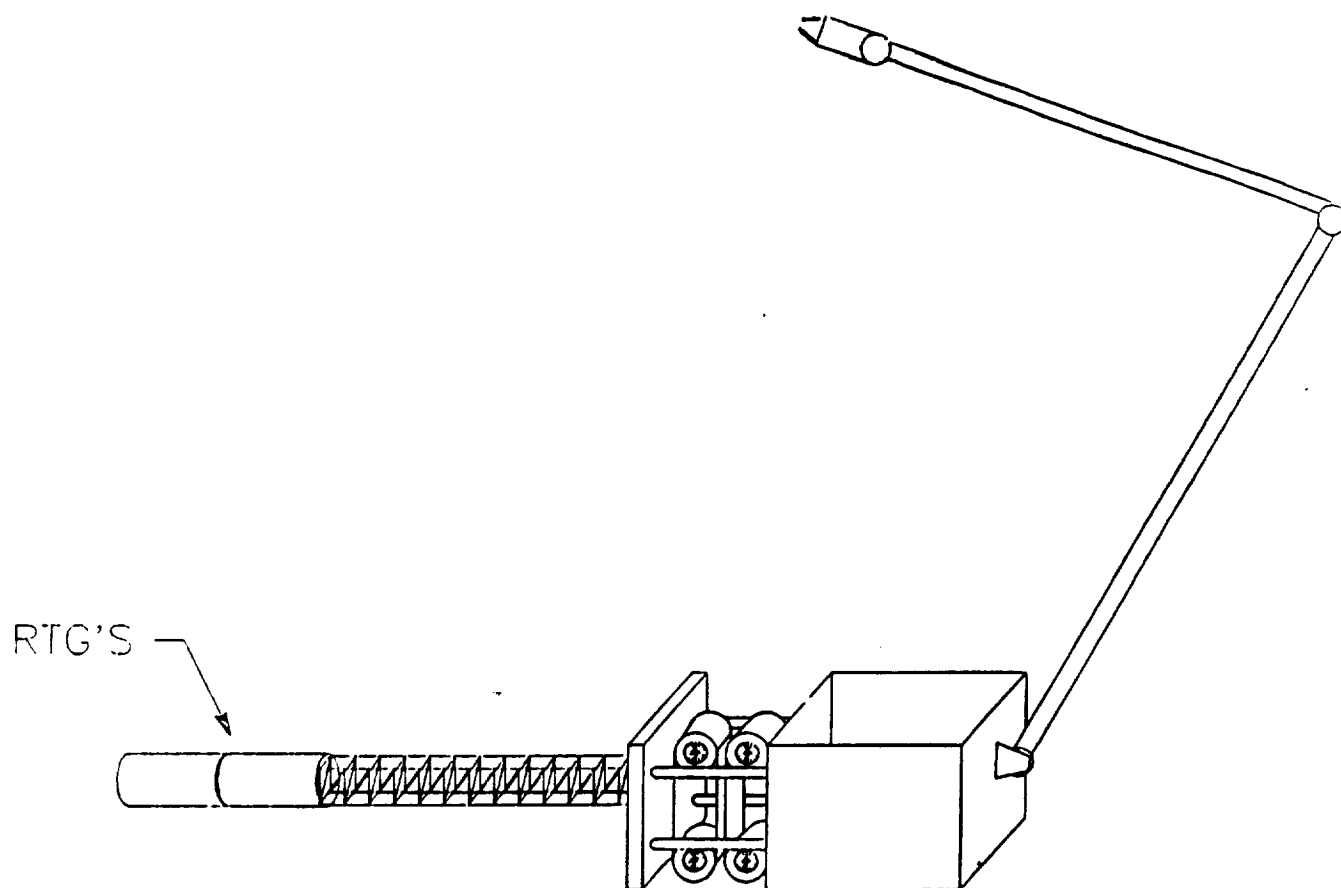


Figure 4.13

## COMPONENT ELEVATOR WITH BATTERIES AND RTG's

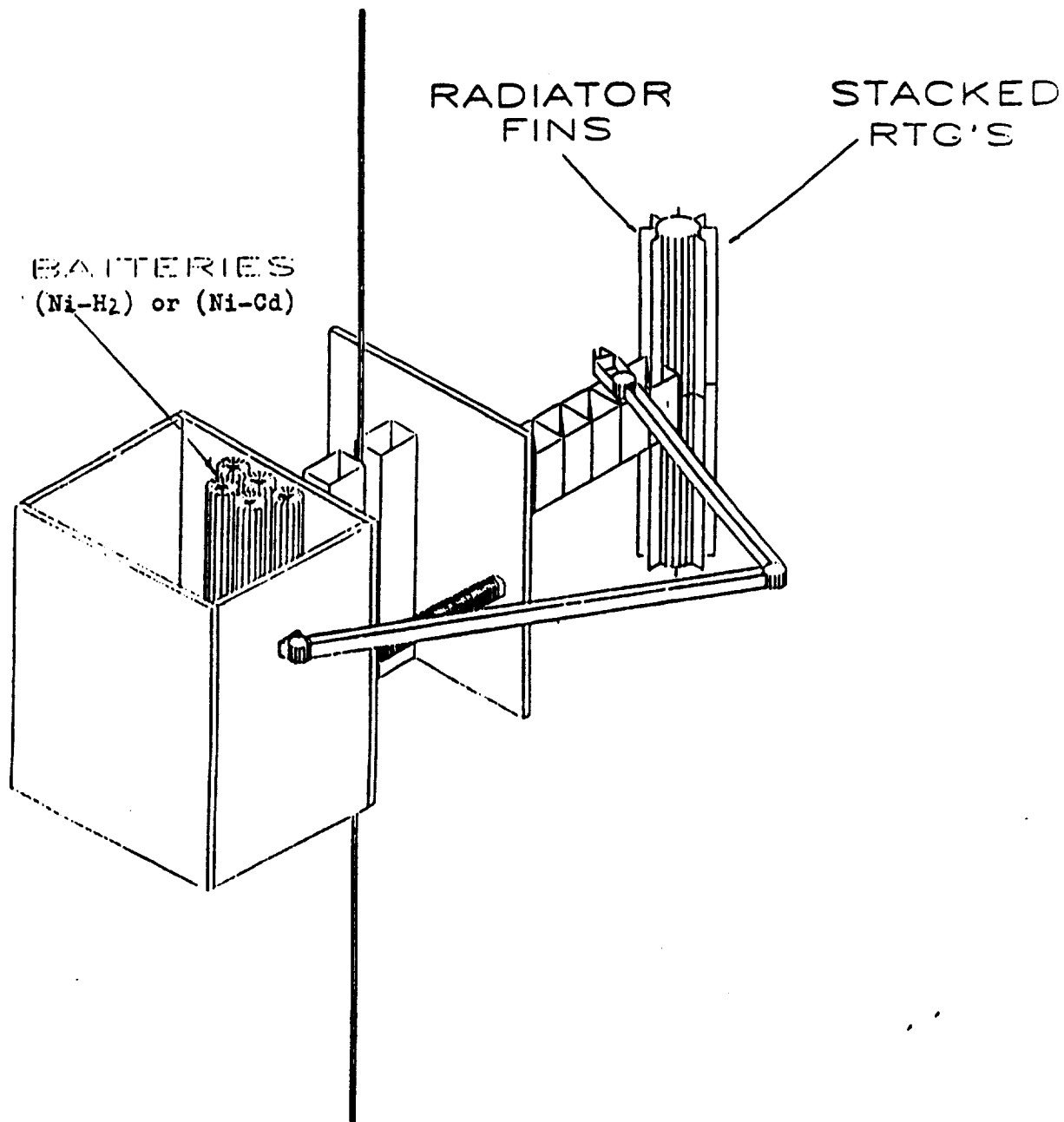


Figure 4.14

## *THERMIONIC ENERGY CONVERTER*

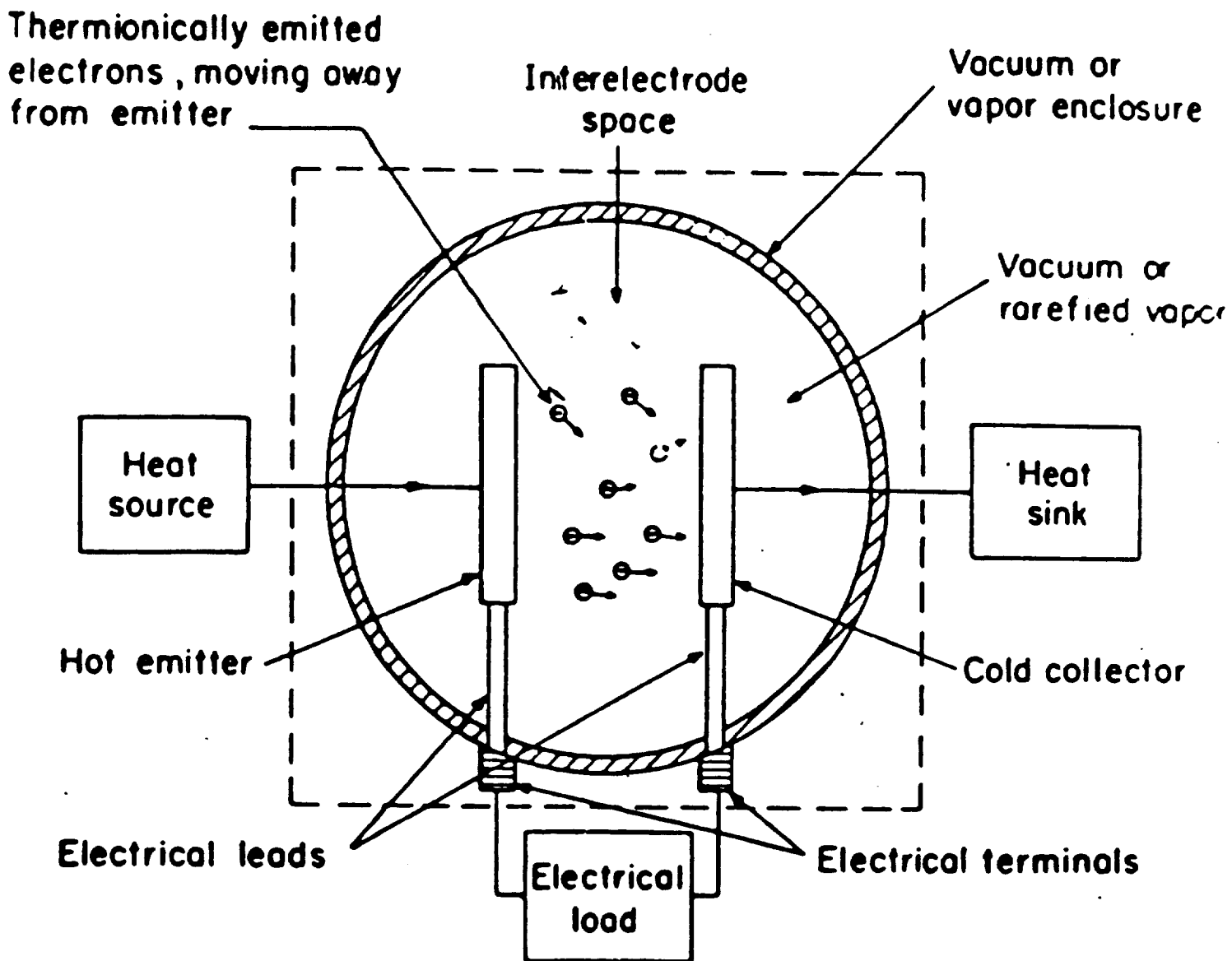


Figure 4.15

of 1700 K or above, and the collector removes heat, through radiation, while being held at a temperature of about 1000 K. [58]

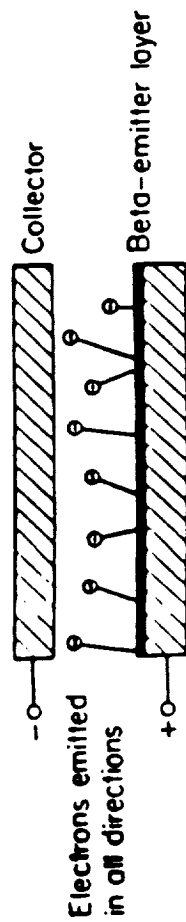
Due to the higher temperature of the thermionic heat radiator, relative to about 573 K for RTGs, at which the collector of the thermionic converter radiates heat, smaller radiator areas are needed to reject the same amount of heat.

Because of their possible size and weight advantages thermionic converters may one day be developed for space applications to the same extent as RTGs. In fact if development continues to receive support, thermionic power conversion technology in space may one day surpass thermoelectrics. At this time, however, thermionic generators fall behind RTGs in the development of space power generators and are therefore not considered the optimal solution for radioisotopic power generation on project LEOTAD.

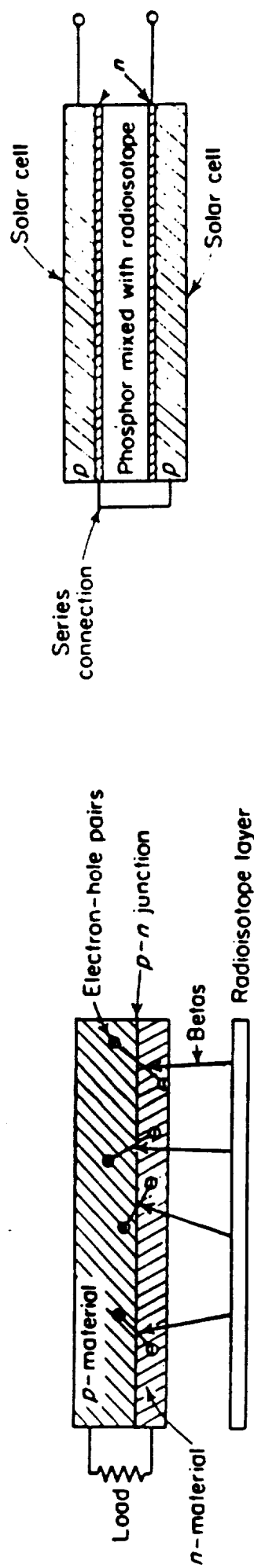
## 42.2 Nuclear Batteries

The second type of energy converters considered for use depend on using the decaying particles of the radioisotope to create electronic excitation. This can be described as a type of nuclear battery. The most direct type of energy conversion system is referred to as primary nuclear batteries. These batteries make direct use of the decaying particles' high energy (See Figure 4.16a). This is achieved by making the charged particles emitted from the radioisotope do work against an electrostatic field. In this configuration two surfaces are separated by a vacuum or dielectric. One plate, the emitter, is coated with a layer of radioisotopes. Charged particles are emitted toward the collector plate then forced through the external load by the electrostatic forces of the particles emitted behind them. One terminal placed on the collector then becomes negatively charged, while another terminal placed on the emitter then becomes positively charged. Thus a potential difference is established.

Another type of power system which generates electronic excitation from decaying particles depends on secondary effects which decaying particles have on matter. Beta particles emitted from radioisotopic decay generate electron-hole pairs in the vicinity of a P-N junction (See Figure 4.16b). The holes and electrons then flow to their proper terminals creating a potential difference. Thus the kinetic energy of the decaying particles is directly converted into electricity through their secondary effect on the semiconductor material. Further possibilities exist when the semiconductor is replaced with an ionized gas between dissimilar plates. The use of the decaying particles to



(a) Primary Nuclear Battery



(b) Secondary Nuclear Battery

(c) Secondary Nuclear Battery with Double Conversion

## NUCLEAR BATTERY SCHEMATIC

Figure 4.16

excite a phosphor which, in turn activates a solar cell, (See Figure 4.16c), is also a possibility for a converter which depends on electronic excitation. These types of converters are generally referred to as secondary nuclear batteries since they are concerned with the decaying particles' secondary effects in matter.

Due to the extensive amount of research and development which has been concentrated on heat engines, nuclear batteries have played a very minimal role in the development of radioisotopic power generation. Except in the microwatt range, their potential as power sources has remained undeveloped. Therefore the cost of increasing the technology of nuclear batteries makes them unsuitable for the relatively higher power requirements of project LEOTAD.

Thus, radioisotopic energy using RTG's for conversion into useable electrical power offers the most beneficial system for generating power and transmitting it to the components on the elevator. Since the RTG's have a relatively long life, are compact, can supply power to the elevator at any given time, and have proven to be highly reliable in other space applications, this design has been chosen as the power generation and transmission system for Design Phase I.

#### Chapter 43. STORAGE

Regardless of the power generation system implemented consideration must be made for an energy storage system. Energy should be stored and ready for use in the event of failure of the primary power source, as well as for components of the system which themselves may require a certain amount of power. Furthermore, a storage system is needed in case the power requirement exceeds the 3.5 kW system designed.

This backup system should make use of any excess power from the primary source to remain charged, and should store enough energy to retrieve the elevator in case of emergency. The storage system must also be capable of salvaging any essential mission requirements which may be jeopardized by break down of the primary power system.

Nickel Cadmium (Ni-Cd), Nickel Hydrogen (Ni-H<sub>2</sub>), or salt batteries can be used to fill this requirement in much the same way as they are used to supply power when solar energy is not available. Silver Zinc batteries have extremely high Watt-hr per lb. characteristics but are not practical for the space elevator because once the power is expended, they cannot be recharged.

There are three major categories that govern the design considerations for batteries. The first category is physical size, weight, and environmental capability. Next is electrical voltage, current loading and duty cycles, noise level, and activation time. The final category involves cost by measuring the battery's shelf life and cycle life. The optimum storage subsystem will consist of Ni-H<sub>2</sub> batteries. The Ni-H<sub>2</sub> batteries are rechargeable, highly reliable, and longer-lived than Ni-Cd batteries. Ni-H<sub>2</sub> batteries promise three times the energy density (energy stored per unit weight) and five times the lifetime of the traditional Ni-Cd batteries. These batteries will improve both the system reliability and the life expectancy of the tethered elevator. According to a standard battery sizing formula, seven batteries with a rating capacity of 50 Amp-hr will be required to meet the elevator needs. The seven cell module (See Figure 4.17) has a dead weight of 23.4 lbs and could be easily mounted on or in the elevator (See Figure 4.14).

The batteries will be interconnected to produce the desired power output and voltage. Then they will be connected to the primary system output so that excess power can be made to flow into the batteries for storage. Furthermore, the output from the batteries will run to the switching regulator to transmit power to the logistic circuitry and control devices, and also to the motor which will control the drive mechanism.

This battery storage system will be utilized on any power system design to lend redundancy to the system as well as supply power in case the capacity of the primary source is insufficient for the load requirement.

#### Chapter 44. POWER GENERATION AND TRANSMISSION SYSTEM OPTIMAL SOLUTION - PHASE I

According to solution matrix operations, the use of radioisotopic energy using modular isotopic thermoelectric generators provide the most efficient method of delivering the needed power to the tethered elevator system. Their reliability, size, power-to-weight ratio and longevity are among its major favorable characteristics. The most sound design would be to mount a minimum of two RTG's on a single short boom which would act as a mounting base and also a counterbalance. Nickel-Hydrogen batteries would provide the most efficient storage/backup power source for the TES. Ni-H<sub>2</sub> batteries are preferred primarily because of their excellent capacity to weight ratio.

## SEVEN CELL NICKLE-HYDROGEN BATTERY MODULE

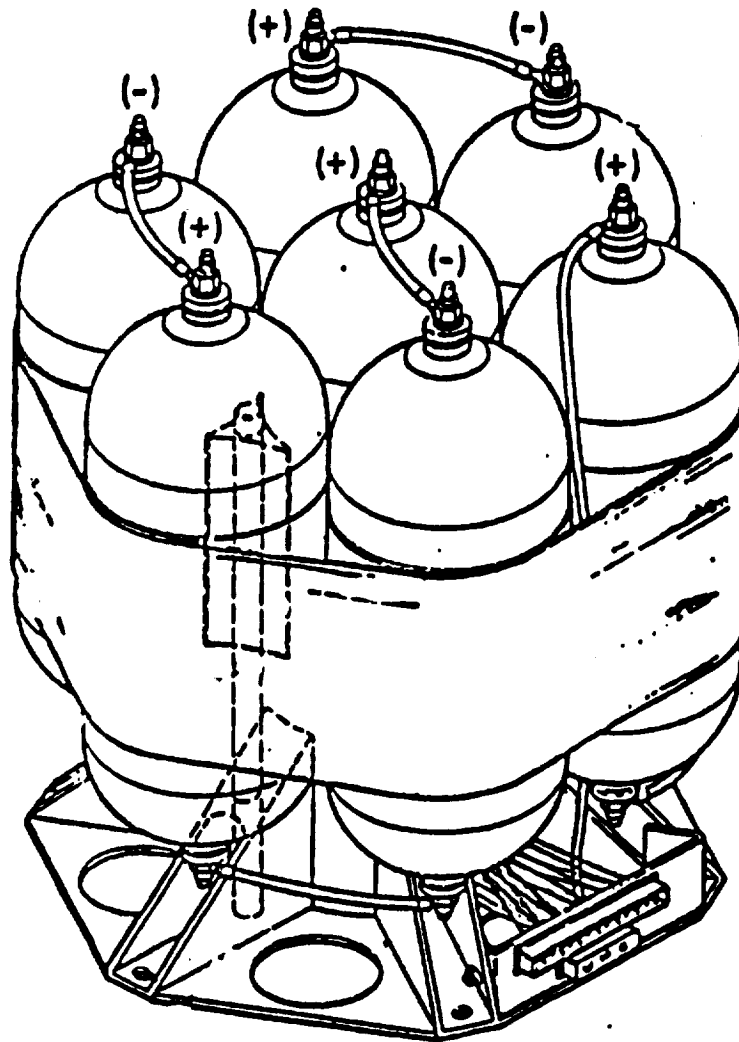


Figure 4.17



## DESIGN PHASE II. POWER GENERATION AND TRANSMISSION SYSTEM

The operating characteristics of the power generation and transmission system must meet certain acceptable standards. Because the radioisotopic energy generators, optimized in Phase I, may impose considerable hazard and risk to SS inhabitants, attention was devoted to identifying alternate methods for generating power.

In this section research is continued for a more attractive power system, a method of transmission of that power to system components, and storage/backup strategies. Included in each method researched is a general description of each system, a discussion of each design and how it may be implemented on the TES. Phase II involves in-depth study in the following areas:

1. Electrodynamic Tether
2. Photovoltaics
3. Microwave Systems
4. Fuel Cells
5. Storage/Backup Strategies
6. Power Transmission Strategies
7. Component Configuration

### Chapter 45. ELECTRODYNAMIC TETHER

A promising alternative for power generation on the TES is the Electrodynamic Tether System (ETS). This orbiting tether system will convert mechanical energy into electrical energy. This process is accomplished by passing the tether through the Earth's geomagnetic field, thus inducing a current within the tether. However, this current is provided at the expense of the system's orbital energy. The tether system has a voltage potential between the two ends in which the circuit is completed through the space plasma via "plasma contactors".

Current is generated in the system when a wire (i.e. the tether) passes through a magnetic field. (See Figure 4.18) As the ETS passes through the ionospheric plasma surrounding the Earth, a charge is collected at one end and emitted at the other (i.e. a charge reservoir and a charge sink). The plasma closes the loop, and a current flow is induced. (See Figure 4.19)

The potential difference in the tether is given by:

$$V = [(\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}] * L$$

where  $\mathbf{v}$  is the system velocity,  $\mathbf{B}$ , the magnetic field of the Earth,  $L$ , the tether length, and  $\mathbf{l}$ , the direction along the

# ELECTRODYNAMIC TETHER PRINCIPLES

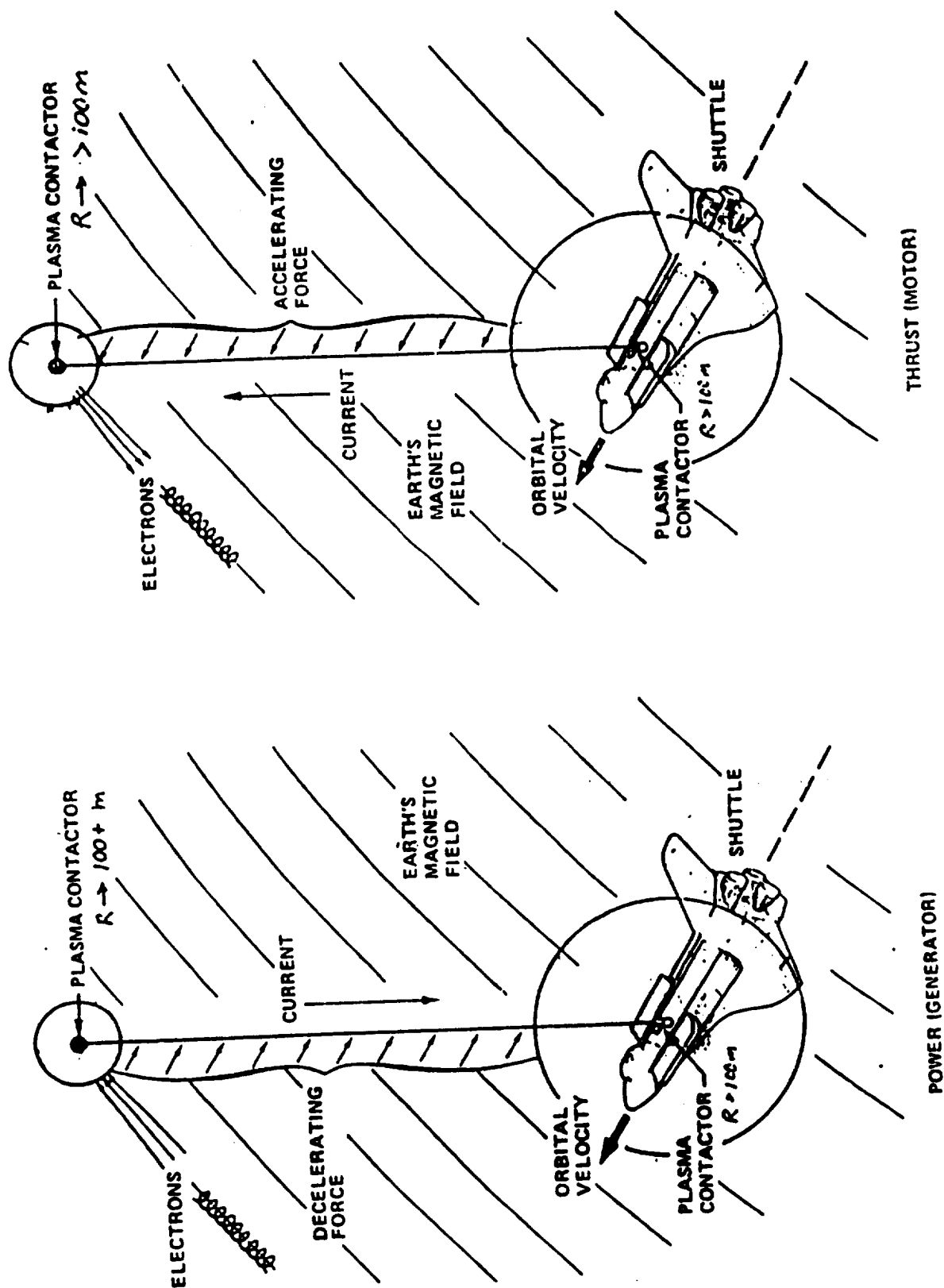


Figure 4.18

## ELECTRODYNAMIC TETHER SYSTEM

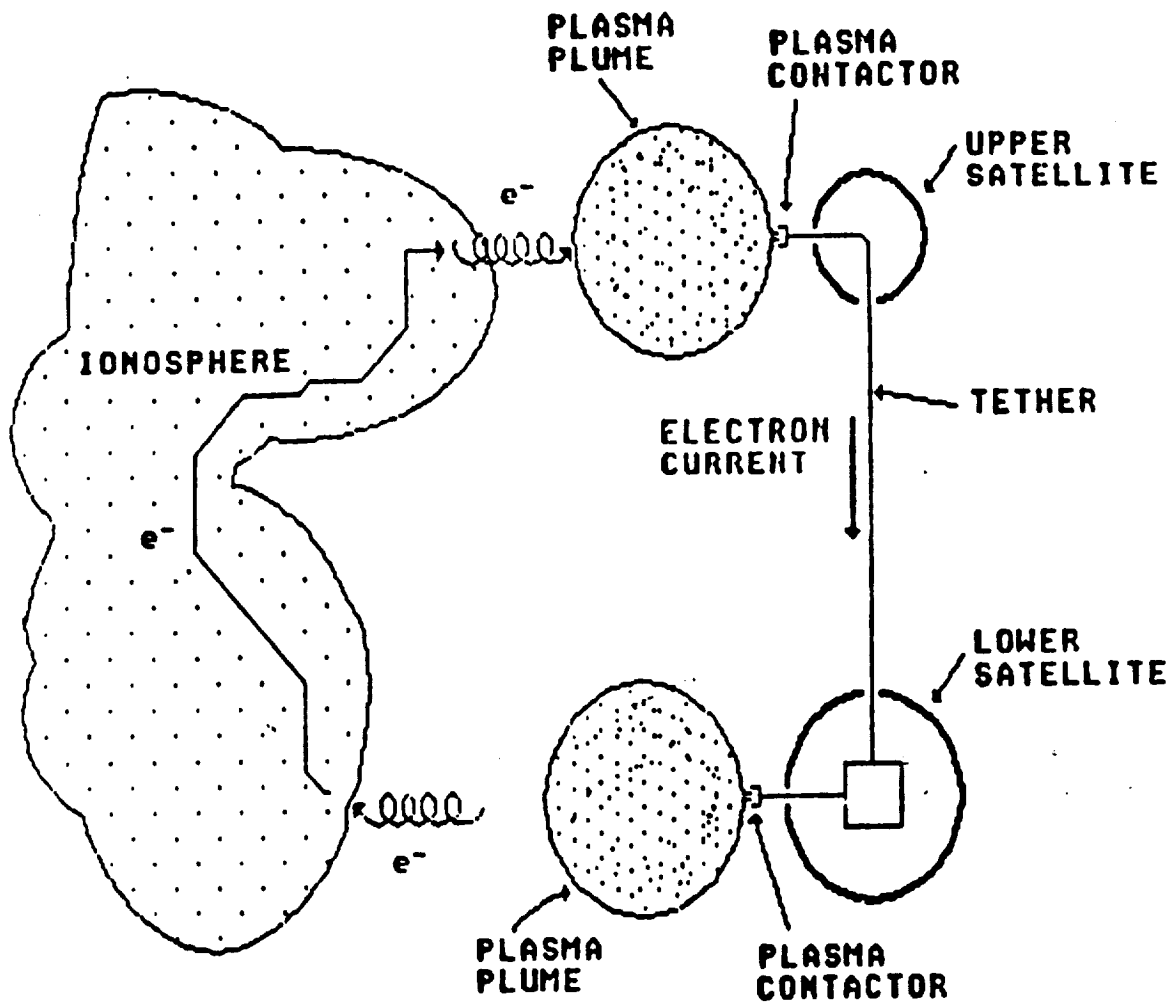


Figure 4.19

tether.[50] However, the current flow within the tether generates an electromotive force (EMF) that opposes the motion of the TES. As a result, an electrodynamic drag acts on the system, thus diminishing the potential orbital energy. Also, an aerodynamic drag is present on the system which contributes to the decrease in the system's orbital energy. However, aerodynamic drag is negligible at altitudes greater than 200 km.

Nevertheless, the operating range of the tether is limited by orbital altitude and the system's angle of inclination with respect to the Earth's magnetic field. Arbitrary limits of 2000 km and inclinations below 60 degrees were chosen. These limits were based on a 25% reduction of a 500 km, low inclination orbit as a reference.[53]

The altitude effects on the ETS are due to two primary causes. The first cause is due to a decrease in geomagnetic field strength that varies inversely with the cube of the orbital radius. The other cause is the decrease in the orbital velocity which varies inversely with the square root of the orbital radius. Since the induced voltage is related to the cross product of the field vector and the velocity vector, then the voltage varies inversely with the 3.5 power of the orbital radius.[53]

As the angle of inclination increases to 90 degrees, the velocity vector parallels the field vector. A zero cross product results and no voltage is induced within the tether. At 60 degrees, the generation capability goes to 25%. Since the Earth's magnetic field is tilted 11 degrees from the Earth's axis, generation will vary from 10-40% of the reference during Earth rotation.[53]

The tether itself must be a high strength cable protected by insulation. The insulation must prevent current leakage and be able to protect against radiation and micrometeorite bombardment. For this reason, it has been proposed that the tether be constructed of Teflon coated aluminum.[59]

The main contributor to the ETS is the plasma contactor. The purpose of the contactor is to transmit and absorb electrons to and from the space plasma surrounding the system. (See Figure 4.20) One of the most promising contactor types is the hollow cathode assembly (HCA). These devices contain a tantalum tube electron beam welded to a tungsten orifice plate. An expellant gas flows through the tube and out the orifice. This expellant collects at an anode, and in the process creates a plasma within the region. [60] This plasma is highly conductive and will provide a sufficient electron density so the tether current can be transmitted [61]. (See Figure 4.21)

## *CONTACTOR PLASMA PLUME REGION*

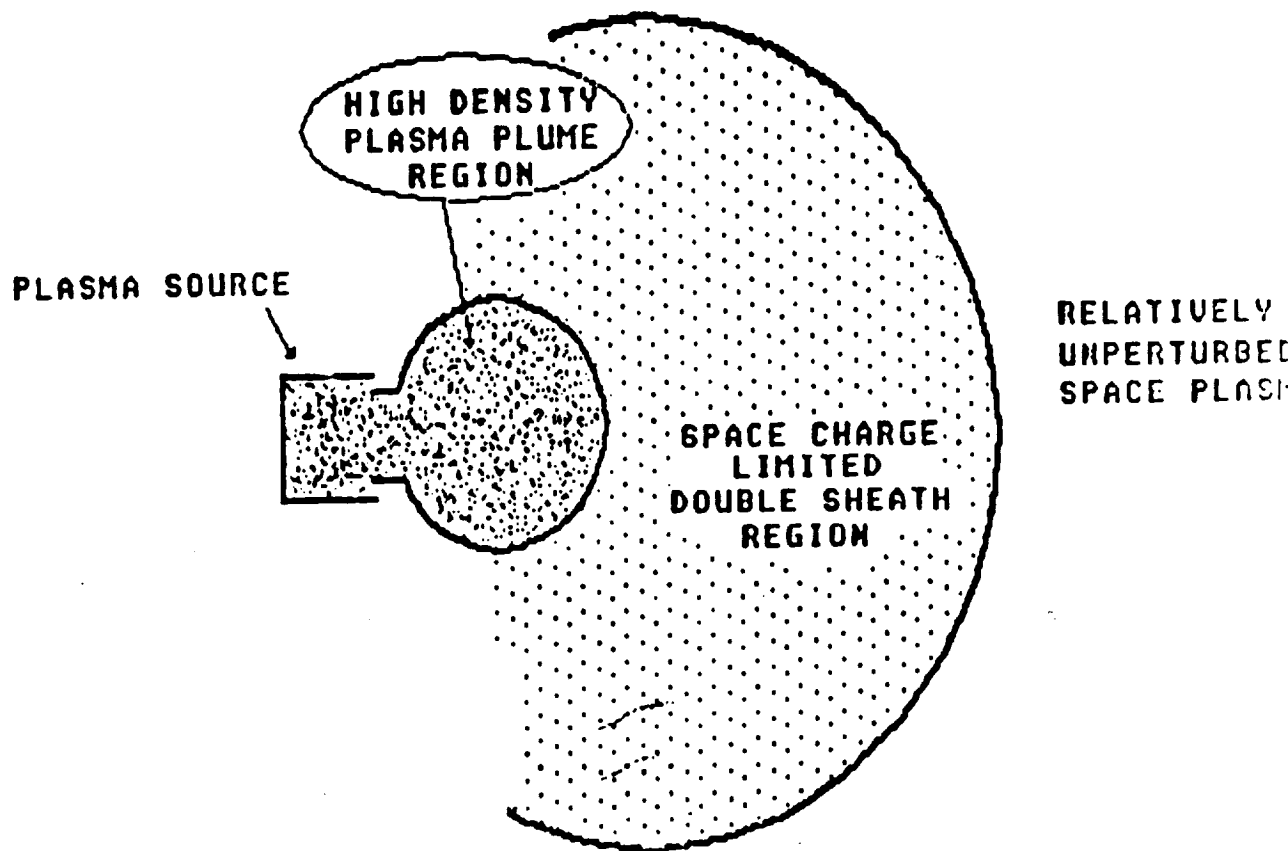
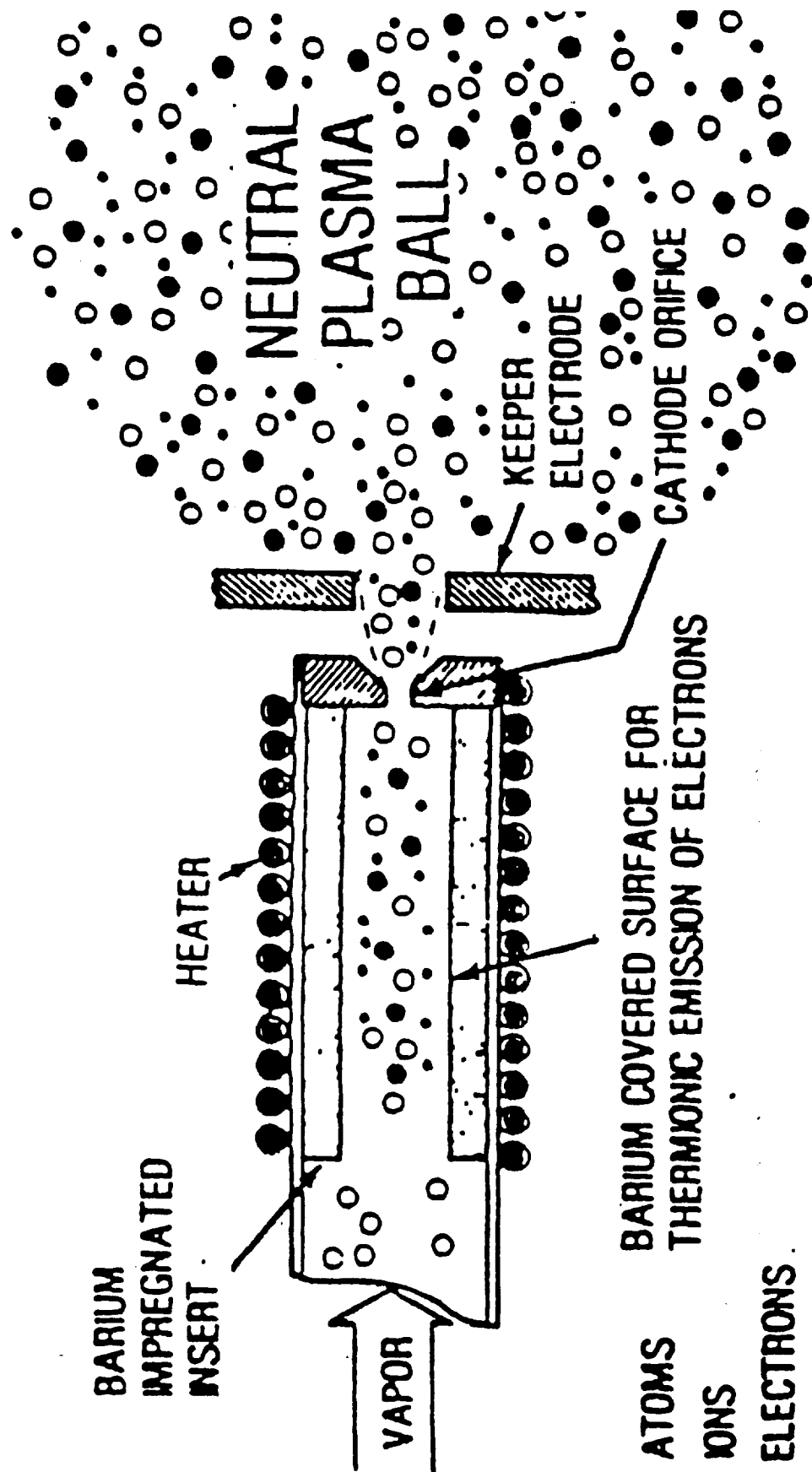


Figure 4.20



STANDARD HOLLOW CATHODE ASSEMBLY

Figure 4.21

Plasma contactors are promising. However, there is one drawback. HCA's have been developed, but further research is required to understand how to contact the tether ends with the plasma.[53] It is believed that this technology will be present by 2010. This report is based on this belief.

The most promising electrodynamic tether design is to use the elevator as a potentiometer. Plasma contactors are attached to the top and bottom of the elevator. (See Figure 4.22) A contactor is also attached at each of the end masses. The system reduces to two smaller circuits. One circuit passes from the top of the elevator to the top end mass. The other circuit passes from the bottom of the elevator to the bottom end mass. As the elevator traverses down the tether, the effective length between the top contactors increases. This increased length yields an increased power. This increased power is desirable since the elevator requires the most power when it is at the bottom of the tether. Conversely, for the elevator to traverse the tether in the opposite direction, the lower contactors will be used. The same principles apply as before.

Power can be transmitted to the elevator in two ways. The first is to attach a wire between the upper contactor and the elevator's contactor. As the elevator moves up and down the tether, the wire can be reeled and unreel as necessary to keep the line taut. This design offers some advantages. First, the design is relatively simple. Second, no further technology needs to be developed. These advantages reduce the cost of the proposed system.

Nevertheless, there are some disadvantages. In this configuration, the wire must be stored on the station. This storage tends to be bulky since the system contains 10 km of wire. Another disadvantage is that the wire can possibly become entangled with the driving tether.

A better design involves the use of a plasma motor/generator (PMG). (See Figure 4.2) In this design, a 20 kW system was proposed. This system was estimated to have an efficiency of 92%. The PMG would use aluminum wire and have an approximate mass of 1200 kg [61]. However, this efficiency may be increased with the use of a different tether. A metal coated Kevlar tether with Teflon and a tight Nomex jacket has a resistance of .058 ohm/ft. For a 10 km tether, this figure translates to an approximate total resistance of 1800 ohms. This decreased tether resistance would reduce the total resistance in the system. Hence, the efficiency would increase. It is unknown at this time what the exact total resistance is so an efficiency cannot be calculated.

## *ELEVATOR CONFIGURATION FOR ELECTRODYNAMICS*

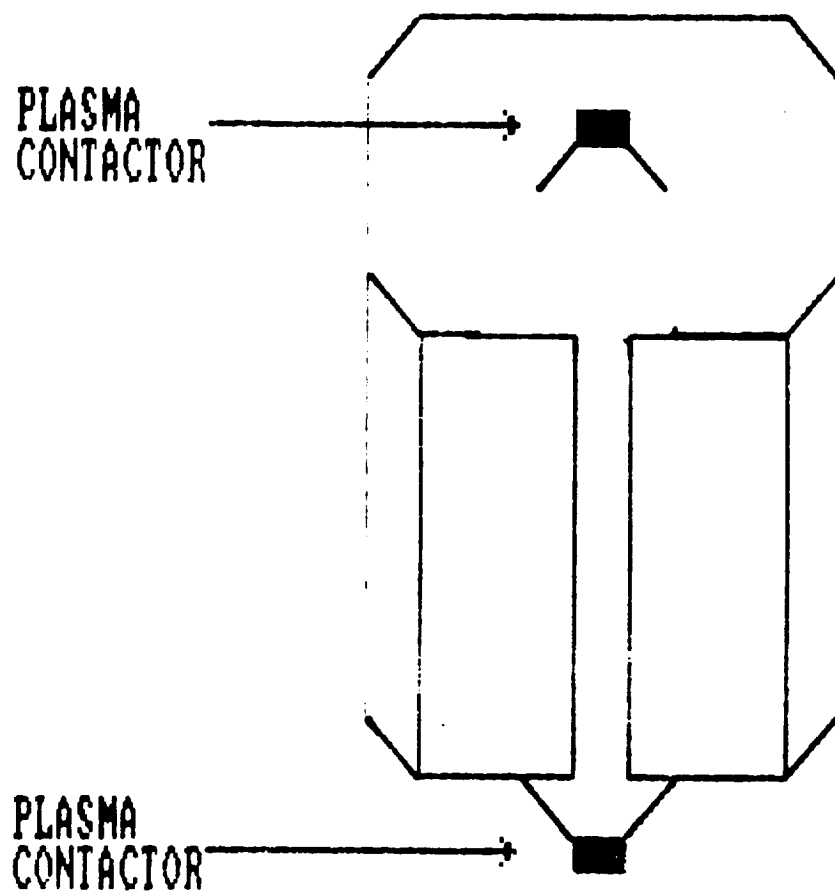


Figure 4.22



The original tether was estimated to carry a maximum current of 14.6 amps and an average current of 10.3 amps. These figures were based on a 25 kW reference system. For a lower resistant tether, the current would not need be as great.

Some disadvantages of the PMG exist. For example, the electrical components still need technological development. Also, the PMG's need to have verification testing. Finally, PMG's must have an alternate power source to operate.[61]

It is believed that technological development will occur by 2010. Likewise, verification testing should be complete at this time. Therefore, PMG's seem a feasible alternative for power generation. It is possible that PMG's be powered by an alternate power system proposed within this report.

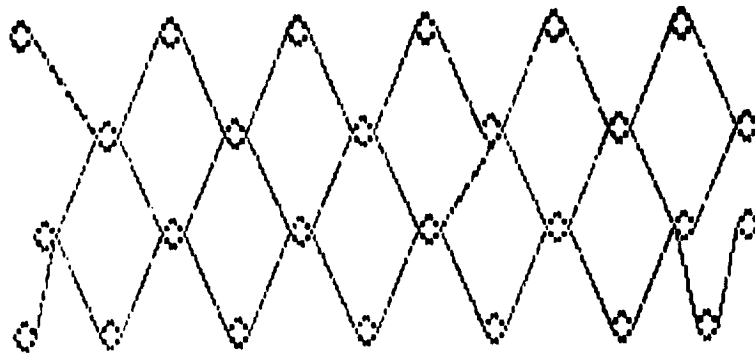
The electrodynamic tether concept is still in experimental stages and offers promising results. With an increased technology, the ETS could be considered a possible source of power generation for the TES.

#### Chapter 46. PHOTOVOLTAICS

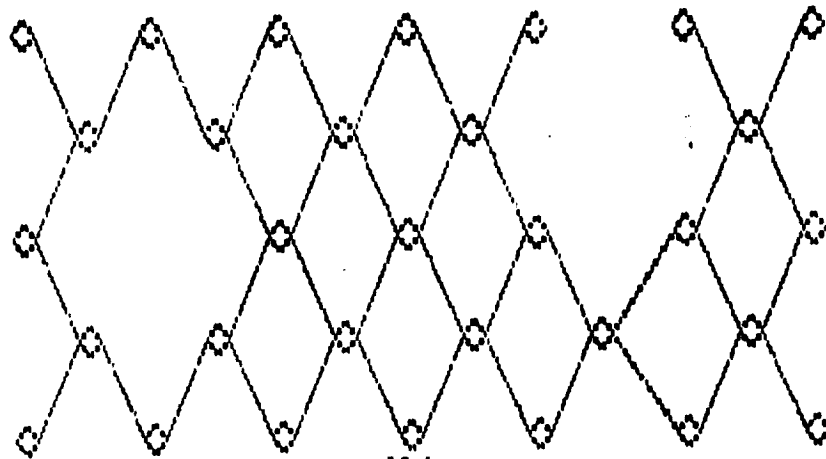
Photovoltaics is the process of converting light into DC power. This feat is carried out by a photovoltaic cell. A photovoltaic cell is a combination of materials to form two semiconducting layers, an n-type and a p-type. A discussion of materials is needed to describe the meaning of these terms.

Many materials can be used to produce a photovoltaic cell, but only the two most common combinations of materials will be discussed here. The most common type of photovoltaic cell is the silicon cell. The silicon atom which has four uncoupled electrons in its outer shell is open to bonding. A pure silicon lattice (See Figure 4.23a) is full and does not permit electron movement. In order to create the electron movement needed to produce electricity a process called "doping" must be performed. Silicon is typically "doped" with Boron creating a lattice such as that in Figure 4.23b. Since Boron has one fewer electron in its outer level, when it is doped it creates electron vacancies commonly referred to as "holes", thus forming a p-type material. Doping introduces a very small concentration of dopant to the parent species. While in processing, the Boron-doped Silicon receives a coating of phosphorous which is sprayed onto the surface. Phosphorous has one more electron than Silicon creating an excess of electrons, thus forming an n-type material.

## ***LATTICE STRUCTURES FOR PHOTOVOLTAIC POWER SYSTEMS***



**(a)**



**(b)**

**Figure 4.23**

Gallium and Arsenide are used to produce the second type of photovoltaic cell that will be discussed. Gallium having only three electrons in its outer level has a lattice such as that in Figure 4.23b, a p-type material. Arsenide has five electrons in its outer level thus giving it an excess of electrons producing an n-type material.

When p-type and n-type materials meet they form what is called a p-n junction. (See Figure 4.24) When the cell is struck by light the electrons are caused to move to the "holes". This movement of electrons across the p-n junction produces electricity.

Many cells connected together form a panel. As the cells are connected the amount of electricity which can be produced is increased. Panels can then be added together to form arrays, which can be added together to produce the amount of electricity needed.

The efficiency of these arrays is determined by the amount of power produced divided by the amount available from the sun. The amount of energy received from the sun is called the solar constant and has a value of  $1.353 \text{ kW/m}^2$ . Typical values for photovoltaic efficiencies on earth range from 16% to 30%, depending on the materials and construction.

The SS will have photovoltaic panels capable of producing 187 kW of power and have an area of 2230 square meters.[62] The efficiency of the system was found to be 5.76%. As compared to earth efficiencies this is a rather low value. There are many reasons for this poor performance. In space there are many hazards which are not present on earth. Micrometeorites are present and are a danger to the photovoltaic panel, as is harmful solar radiation which is filtered out on Earth by the atmosphere. Protection against such hazards must be established and with the protection comes a reduction in efficiency. There will be further reduction in efficiency of the array over time, this is called degradation and is caused by radiation affects that cannot be shielded against.

Photovoltaics is an option for providing power to the tethered elevator system. Using the efficiency developed of 5.76% it has been determined that 150 square meters of photovoltaic cell array will be required to produce the 10 kW of power with some redundancy to go to the storage system for use on the dark side of the orbit. Placing the arrays of this size on the body of the tethered elevator system would not prove feasible because the area is needed for functions. Therefore, it would seem to be a better solution to place two 75 square meter arrays on either side of the elevator on arms with four degrees of freedom. (See Figure 4.25) This would leave the area on the elevator free for other functions.

## *P-N JUNCTION FOR PHOTOVOLTAIC POWER SYSTEMS*

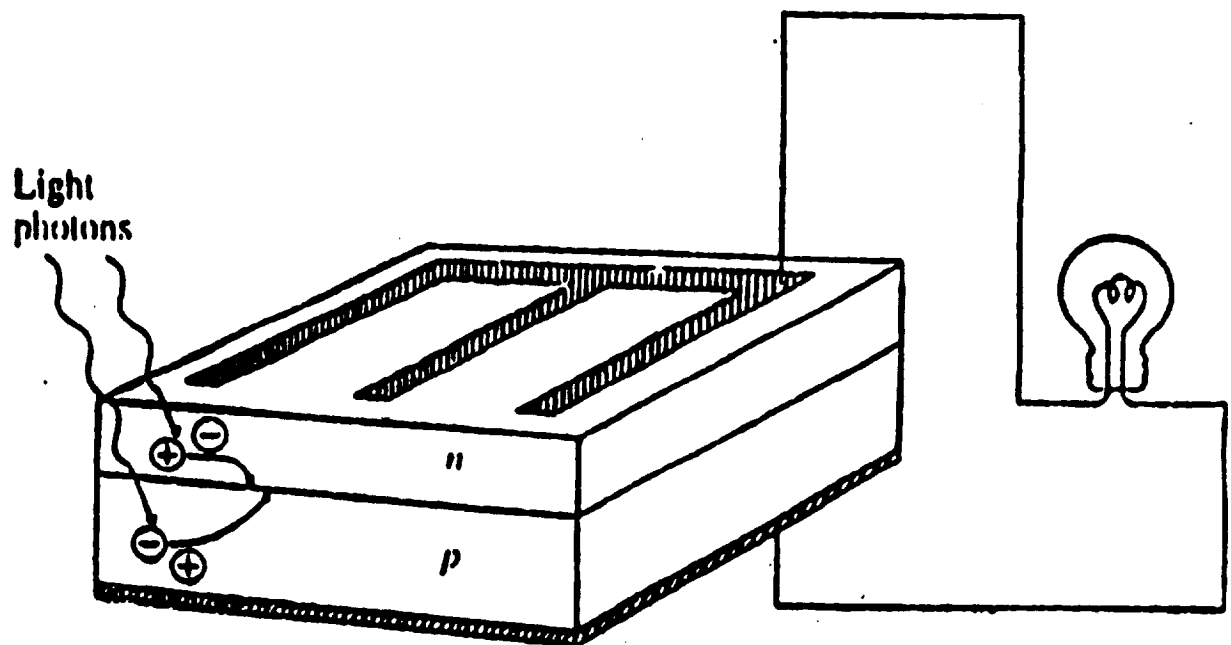


Figure 4.24

*ELEVATOR WITH  
PHOTOVOLTAIC PANELS*

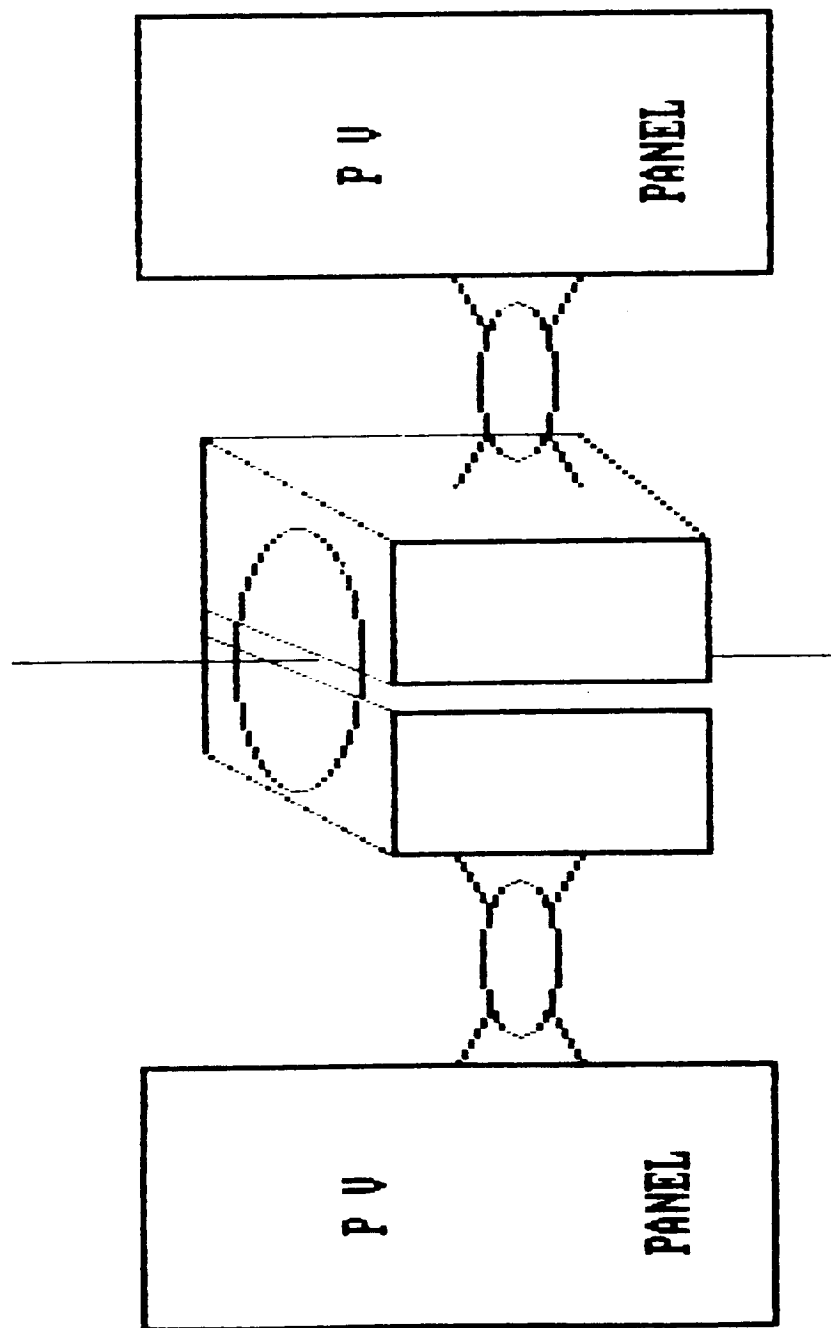


Figure 4.25

Tracking of the Sun could be accomplished with gas cylinders placed on all four sides of the arrays. Systems such as these are commonly used in terrestrial applications. When the array becomes out of align with the sun the gas cylinder on one side of the panel gets hotter requiring more volume and transfers some of its mass to the cooler cylinder thus leveling the panel in line with the sun.

The disadvantages of this system are added weight to the tethered elevator, the drag and subsequent loss of orbital energy, and area it would require on the elevator. Advantages would include reliability, feasibility and safety.

Photovoltaics could be used in conjunction with a microwave transmission system to remove many of the disadvantages previously mentioned. This in turn would produce a large array size on the Space Station, 2140 square meters, approximately doubling the array area currently proposed to power the SS. This could prove to be a disadvantage that would have to be weighed against the advantages discussed in the section on microwaves.

#### Chapter 47. MICROWAVES

The transmission of power through the use of microwaves is not a new concept. The idea was conceived in the early twentieth century by such people as Heinrich Hertz and Nikola Tesla. Tesla was quoted in a 1928 Popular Science article as saying that someday airplanes would be "powered by wireless" [64].

The power that was able to be transferred through the use of microwaves was very small at first, only on the order of milliwatts. During WW II this amount was greatly increased by the development of first the klystron tube and then magnetrons. Magnetron technology is currently used in microwave ovens which are used in many homes.

Microwaves are, by definition, very short wavelengths, on the order of a few centimeters. They also have very high frequencies, approximately 2.5 gigahertz. Unlike other waves, radio waves for example, which travel in all directions, microwaves are easily focused due to the aforementioned characteristics.

Transmission of microwave power is done in much the same way as communications. A transmission antenna is placed near a power source. The antenna not only acts for transmission but also to focus the power beam on the target. On the target is a receiving antenna which receives the transmitted power. A receiving antenna designed by William C. Brown coined "rectenna" is so called because it is a rectifying

antenna.[64] It receives the AC power, at a rate of 500 watts per square meter, from the transmitter and converts or rectifies it into DC power. This feat is accomplished by hundreds of dipole copper elements etched into the "rectenna" surface. Each of these elements is connected to four diodes.

Diodes in William C. Brown's system are constructed of gallium arsenide (GaAs) but other systems now use silicon (Si). Each material has its own advantages and disadvantages. GaAs has sixteen (16) times the power conversion capability of Si (4 watts as opposed to .25 watts) while costing forty (40) times as much. GaAs is also much noisier than Si.

A distinct disadvantage of this system is its low efficiency. When 500 kW are transmitted only 30 kW will reach the motor.[64] These figures produce an efficiency of only 6%, which is much higher than the efficiency according to Dr. Ronald E. Barrington, director of communications technology research at the Canadian Government's Communications Research Centre (CRC), of only 2%.[65] Theory predicts that in order to create a 30 meter diameter spot at an altitude of 21336 meters it will require a 70 meter diameter antenna at the power supply.

This system has an advantage of being extremely safe and non-disturbing to the surroundings. Joe Schlesak, a team leader for the CRC, said "If you were sitting on the beam up there (21336 meters) you'd feel a slight warming sensation ... the power level at any point above the antenna is safe, below national safety standards." [64]

The Stationary High-Altitude Relay Platform (SHARP), which is the CRC's microwave power project, was flown "under radio control with an unmodified receiver on board" according to Schlesak.[64] This would seem to say that it would have no effect on communication systems.

The preceding applications of microwaves have been terrestrial, but according to Robert Forward, recently retired scientist from Hughes Research Laboratories, no further scientific breakthrough will be needed for applications in space. Forward has made calculations for a probe called "Starwisp" which, using microwave power transmission, could accelerate to one-fifth the speed of light and reach Alpha Centuri in 21 years. This would require a transmitted power from Earth of 10 gigawatts.[64]

Microwaves could be used to provide power for the tethered elevator system. The proposed application could place a power source on an unused portion of the Space Station with a transmission antenna nearby. The power could then be transmitted to the tethered elevator system where a

receiving antenna "rectenna" would be located. Calculations using a 6% efficiency (this is the highest efficiency available to provide for technological advances) show that 167 kW of power would have to be produced on the Space Station to receive the design requirement of 10 kW on the tethered elevator system. Although this power production level seems to be prohibitive and could be a disadvantage to microwave transmission, the power supply will be located on the Space Station and could be used, when the tethered elevator system is not in operation, for Space Station applications.

#### Chapter 48. FUEL CELLS

Most forms of energy that the earth's population utilizes is initially derived from energy which has been stored within the chemical bonds of hydrocarbon fuels such as coal, gasoline, and natural gas. According to the second law of thermodynamics, when energy is converted into electrical power most of it is discarded. The maximum amount of useful power that can be obtained from this energy is limited by the Carnot engine cycle. For this reason, the various conversion processes of real power plants limit their overall thermal efficiencies to, at best, 40 percent.

Fuel cells offer a means of conversion that eliminates the high temperature combustion and subsequent processes found in nearly all energy conversion schemes designed to produce electrical power. A fuel cell is an electrochemical device that continuously converts the chemical energy of a fuel and oxidant into electrical energy. Since the conversion cycle is electrochemical, rather than thermal, fuel cells are not subject to Carnot cycle limitations.[63] This offers highly efficient conversion into electrical energy. The essential difference between fuel cells and batteries is the continuous nature of the fuel supply. The fuel and oxidant, which is usually oxygen, is supplied continuously to a fuel cell from an external source. In a battery, the fuel and oxidant are contained within and once they have been consumed, the battery must be replaced or recharged.

Fuel cells utilize liquid or gaseous fuels, such as hydrogen, hydrazine, hydrocarbons, and coal gas. The oxidant in a fuel cell is gaseous oxygen or air. A practical fuel cell power plant consists of at least three basic subsystems: [66] (See Figure 4.26)

1. A power section which consists of one or more fuel cell stacks - each stack containing many individual fuel cells connected in series to produce a stack output ranging from a few to several hundred volts



# BASIC FUEL CELL POWER PLANT

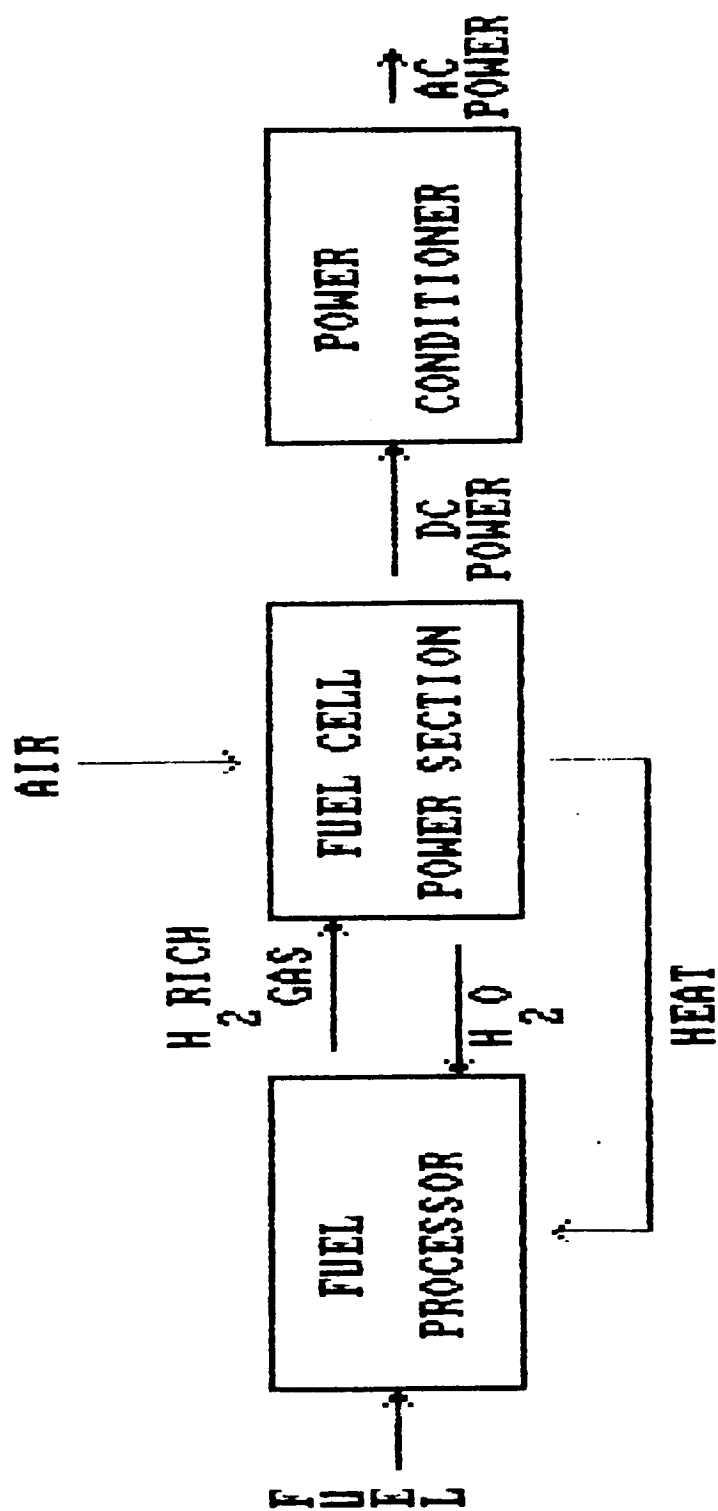


Figure 4.26

(direct current). This section converts processed fuel and oxidant into DC power.

2. A fuel processor that manages the fuel supply to the power section. This subsection can range from simple flow controls to a complex fuel-processing facility. This section processes fuel to the type required for use in the fuel cell power section.
3. A power conditioner that converts the output from the power section to the type of power and quality required by the application. This section could range from a simple voltage control to a sophisticated device that would convert the DC power to an AC power output.

Depending on the size, type, and sophistication, a fuel cell power plant may require an oxidant subsystem as well as thermal and fluid management subsystems.

Although fuel cells were invented nearly 150 years ago, their first practical application did not come until the 1960's as a spacecraft power source for Gemini and Apollo missions. They are classified as power generators because they can operate continuously, or as long as fuel and oxidant are supplied, and are rated by the kilowatt of power output. Today, fuel cells are able to provide power for extended missions. Future applications will include remote power generation (space, undersea), military, commercial electric power generation (by both electric and gas utility industries), and possibly, in the longer range, hybrid electric vehicles.

Efficiencies of a fuel cell are essentially independent of size; small power plants operate nearly as efficiently as large ones. Fuel cell power plants are quiet and clean, the by-product being water. For this reason they are attractive for an application on the TES since noxious emissions and noise would be objectionable. The water produced by the fuel cells may be utilized in coordination with the balance of the elevator and is also potable. Due to their small size and modularity, they are very attractive for remote locations.

As stated earlier, the fuel cell is similar to that of a battery with its primary differences being the continuous nature of energy supply. A fuel cell produces energy through an electrochemical reaction between two catalyzed carbon electrodes which are immersed in an electrolyte and separated by a gas barrier. A simple fuel cell is illustrated in Figures 4.27 and 4.28. The fuel, in this case hydrogen, is bubbled across the surface of one electrode while the oxidant, in this case oxygen, is bubbled across the other electrode. When these electrodes are electrically connected

## SIMPLE FUEL CELL

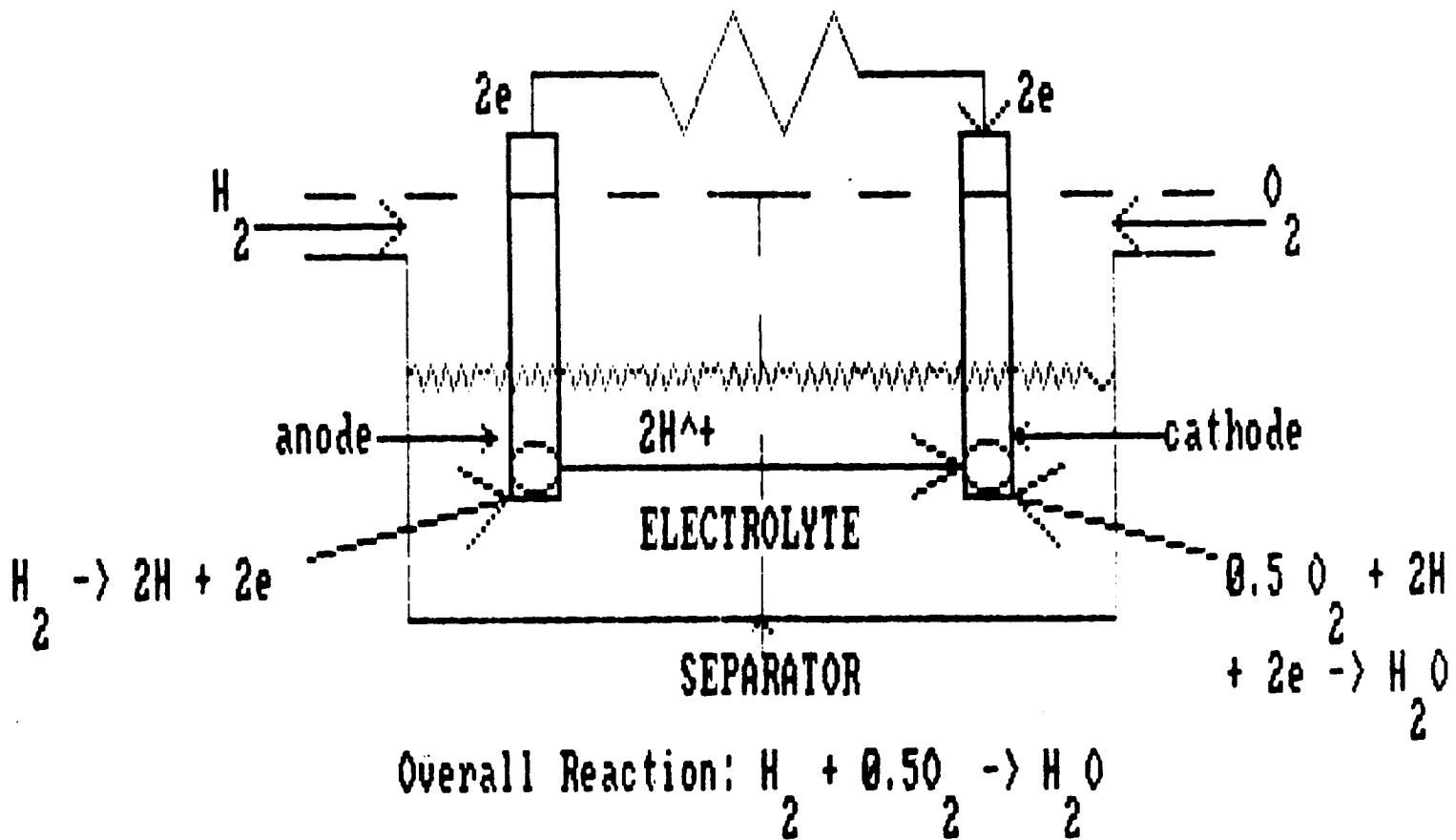


Figure 4.27

## SIMPLE FUEL CELL CONSTRUCTION FEATURES

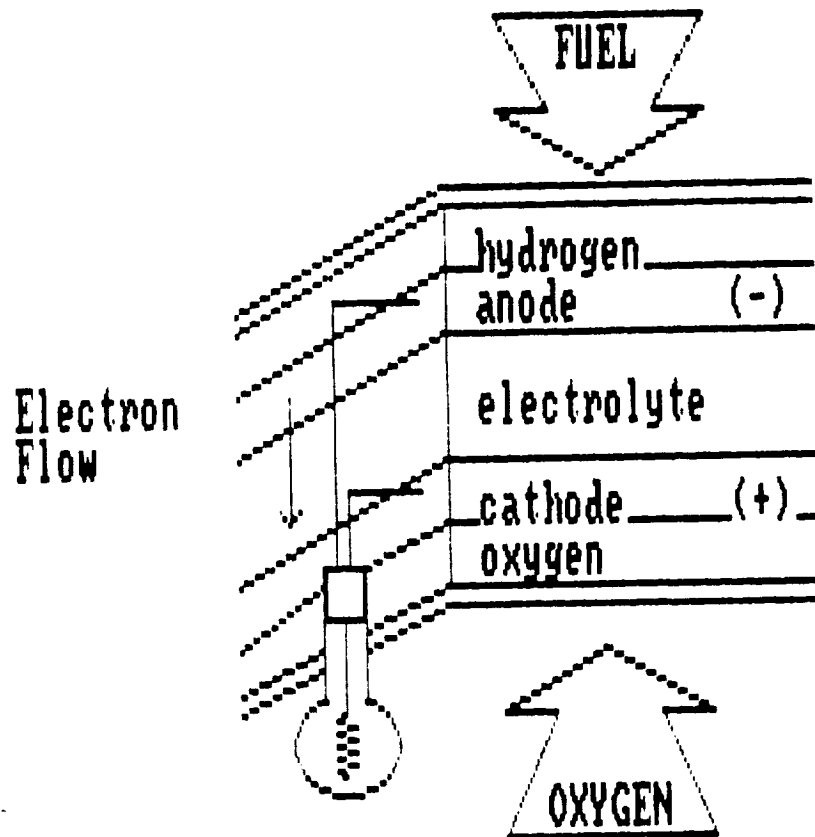


Figure 4.28

through an external load, the following events occur:

1. The hydrogen dissociates on the catalytic surface of the fuel electrode, forming hydrogen ions and electrons.
2. The hydrogen ions migrate through the electrolyte (and the gas barrier) to the catalytic surface of the oxygen electrode.
3. Simultaneously, the electrons move through the external circuit to the same catalytic surface.
4. The oxygen, hydrogen ions, and electrons combine on the oxygen electrodes catalytic surface to form water.

The reaction mechanisms of a hydrogen/oxygen fuel cell are shown here:

ANODE:  $\text{H} \rightarrow 2\text{H}^+ + 2\text{e}^-$

CATHODE:  $0.5\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$

OVERALL:  $\text{H}_2 + 0.5\text{O}_2 \rightarrow \text{H}_2\text{O}$

The net reaction is that of hydrogen and oxygen producing water and electrical energy. As in the case of batteries, the reaction of one electrochemical equivalent of fuel will theoretically produce 26.8 AMP-hours of DC electricity at a voltage that is a function of the free energy of fuel-oxidant reaction. At ambient conditions, the potential is ideally 1.23 V DC for a hydrogen/oxygen fuel cell.[66]

The important components of the individual fuel cell are the anode (fuel electrode), which must provide an interface for the fuel and electrolyte, catalyze the fuel oxidation reaction, and conduct electrons to the external circuit. The cathode (oxygen electrode) must provide an interface for the oxygen and electrolyte, catalyze the oxygen reduction reaction and conduct electrons from the external circuit to the oxygen electrode reaction site. Finally, the electrolyte must transport the ions involved in the fuel and oxygen electrode reactions while preventing the conduction of electrons. If electrons were to be conducted through the electrolyte it would cause a short circuit. Other components may be required to seal the cell, provide gas compartments, or separate one cell from the next in a fuel cell stack.

Most fuel cell power plants are of a bipolar configuration because of their simplicity. In this configuration, cells are placed electrically in series by the

electronically conducting separator located between the anode and cathode of adjacent cells. The advantage in this type of configuration is that no external connections are required to electrically connect individual cells.

Fuel cell systems can be classified into either direct or indirect fueled systems. In a direct fuel cell, the fuel used is readily oxidized electrochemically in the fuel cell and is fed directly. In the indirect system, the fuel must first be converted in a fuel-processing subsystem to an easily oxidized hydrogen-rich gas, which is then fed into the fuel cell. For remote applications, such as space and undersea, the logical fuel type is direct hydrogen or hydrazine coupled with oxygen.

Low Power fuel cell systems were designed mainly for these type of military or special applications such as the space program [67]. They are particularly advantageous because of their ease of operation, low maintenance, and silence which are all important constraints of an elevator power system. Fuel cells for space application offer high energy densities that exceed the performance of batteries when operated over long periods of time. Figure 4.29 compares the performance of typical primary and secondary batteries with fuel cell systems and shows their weight advantage for long-term operation.[68]

Various fuel cell systems have been used for past space applications. The systems built between 1960 and 1970 for the Gemini and Apollo space programs and in 1980 for the Space Shuttle Orbiter are among the most successful demonstrated to date. Their designed power output was 1 kW, 1.5 kW, and 7 kW respectively.[69] Each of these systems used Hydrogen as the fuel, Oxygen as the oxidizer, and were direct-type fuel cells. The Bacon hydrogen/oxygen fuel cell technology, as utilized on the Apollo, and as utilized on the Space Shuttle Orbiter with significant design advances, will serve as the basis for our proposed system design.

A fuel cell power system, similar to that currently used on the Orbiter, could be used for the tethered elevator. The power plants used on the Space Shuttle Orbiter are 20 kg lighter and deliver 6 to 8 times as much power as those of the Apollo system.[70] The Orbiter system is made up of three fuel cell power plants and normally supplies 14 kW of power, with peak loads of 36 kW. Each power plant is 35cm high, 38cm wide, and 101cm long and weighs 92kg (approximately 202 pounds).[70] Each fuel cell power section contains two parallel stacks of 32 cells in series. Hydrogen fuel and oxidant are cryogenically stored and delivered to each fuel cell. On a 3-day mission, the fuel cells utilize about 450 kg of H<sub>2</sub> and O<sub>2</sub>; about 600 liters of water are produced.

## COMPARISON OF ELECTROCHEMICAL SYSTEMS WEIGHT VS. SERVICE LIFE

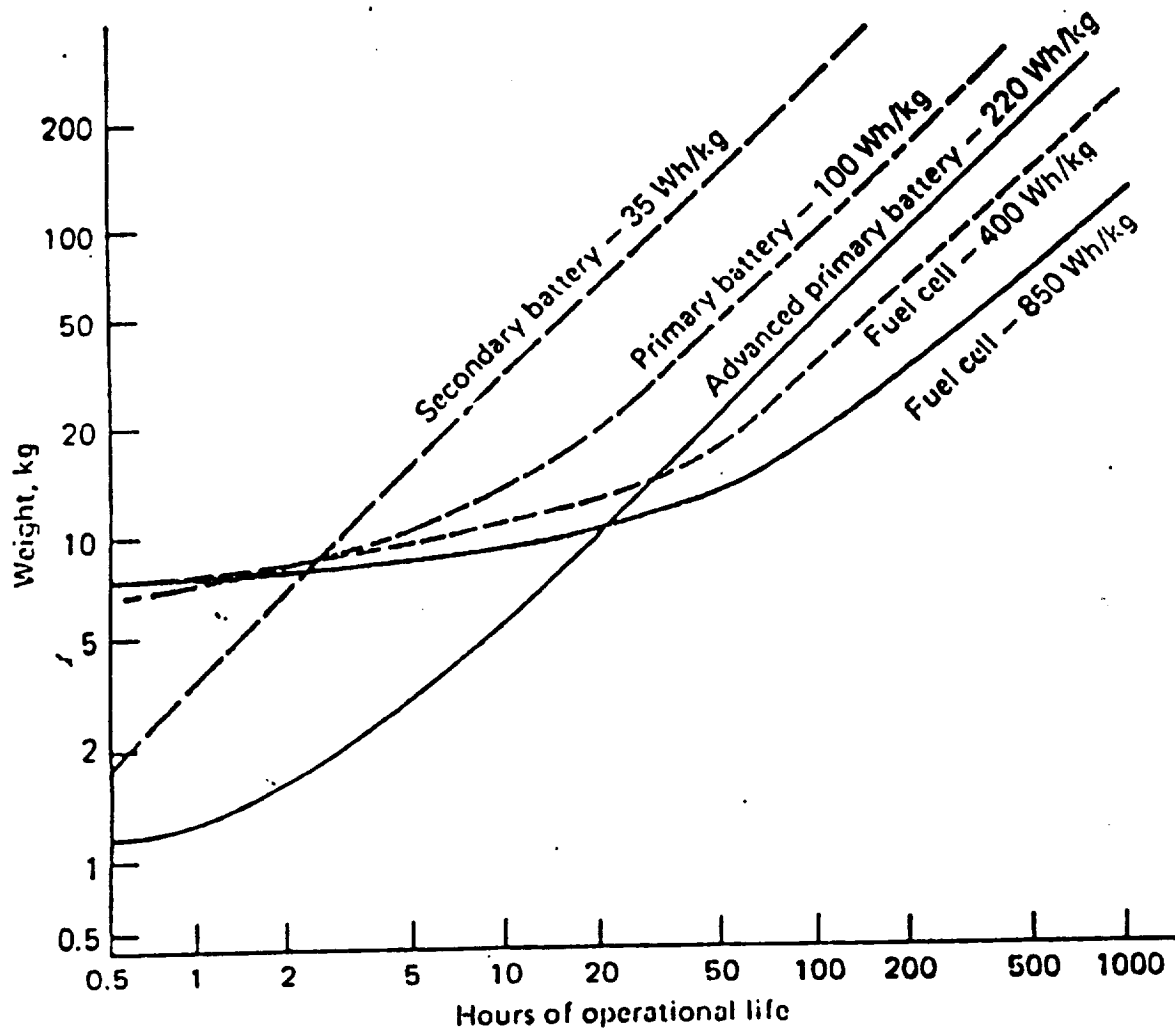


Figure 4.29

The proposed fuel cell power system for the TES will consist of a single power plant. It will be a hydrogen/oxygen system with a potassium hydroxide (KOH) electrolyte. Each cell uses magnesium separator plates for rigidity of electron transfer paths, and water and waste heat removal. In order to provide the needed 10 kilowatts of power and minimize its size, it will consist of one stack of cells divided electrically into parallel substacks of 32 cells each. This system will be able to provide 2 kW minimum, 7 kW continuous, and 12 kW peak power. The fuel cell stack will be equipped with an accessory package to handle reactant management, thermal control, water removal, electrical control, and monitoring. This accessory package is located at one end of the power plant stack and can be separated from the cell stack for easy maintenance.

The hydrogen and oxygen required for the fuel cell must be cryogenically stored in a supercritical condition (97K or -285 degree F for oxygen and 22K or -420 degree F for hydrogen).[70] In this supercritical condition, the hydrogen and oxygen takes the form of cold, dense, high pressure gas that can be expelled, gaged (quantity measured), and controlled under zero-g conditions. For this type of storage, double-walled vacuum-jacketed Dewar-type spherical tanks are necessary. Each tank must have a relief valve to prevent overpressurization, an automatically activated heater for start-up, and a shutoff valve.

The size of the fuel and oxidant tanks can vary depending on the amount of trips the elevator will be required to make and on expected usage rates (See Table 4.1). From these two parameters the tank characteristics can be designed, i.e. total capacity, maximum pressure, added weight, and diameter (See Table 4.2). They should be designed such that they can be easily refueled from a storage tank located on the Space Station, as they become low or empty. It would be desirable to accomplish this through the use of the robotic arm, in order to keep extravehicular activity to a minimum.

The proposed fuel cell power plant design will be contained within a 6 x 6 x 5 cubic foot area. The power system will utilize 3 oxygen tanks and 3 hydrogen tanks. The oxygen tanks will be 7.87 inches in diameter and hold 183.3 lbs. of oxidant. The hydrogen tanks will be 15.2 inches in diameter and hold 22.9 lbs. of fuel. Coupled together by a simple fuel regulator system (Figure 4.30) these tanks will provide 168 hours of continuous operation.

Fuel cells are a proven power source in space and appear very attractive for the stringent requirements of the TES. Its many advantages include extremely good efficiencies, since it is not subject to Carnot cycle limitations, at



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## ***FUEL CELL CRYOGENIC USAGE AND WATER PRODUCTION***

	HYDROGEN USAGE lb/amp-hr	OXYGEN USAGE lb/amp-hr	WATER PRODUCTION lb/amp-hr
Theoretical	0.0027	0.0212	0.0238
Ground Test	0.0029	0.0252	0.0253
Flight Data	0.00275	0.0220	0.0245
* Based on average calculated rates taken from 15, 24, 30, and 34.5 hours of operation.			

**Table 4.1**

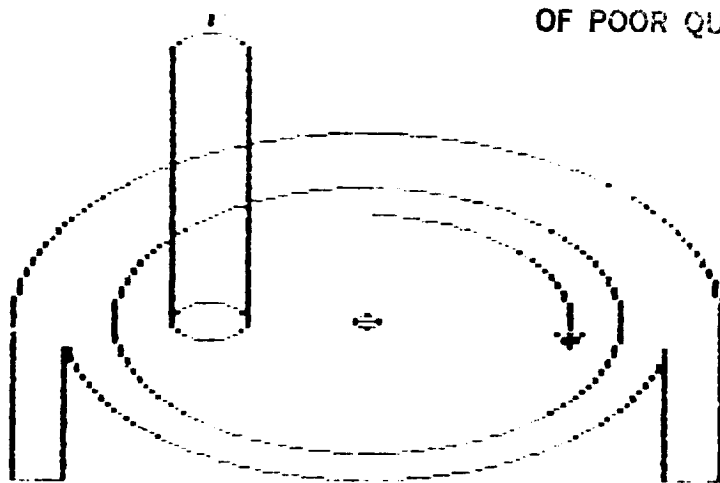
## FUEL / OXYGEN TANK CHARACTERISTICS

Time									
Days	Hrs	Amo-Hrs of Operation	H <sub>2</sub> Needed (lbs.)	O <sub>2</sub> Needed (lbs.)	Water Produced (lbs.)	H <sub>2</sub> Tank Diameter (in.)	H <sub>2</sub> Tank Capacity (cu. Ft.)	O <sub>2</sub> Tank Diameter (in.)	O <sub>2</sub> Tank Capacity (cu. Ft.)
0.28	6.72	1000	2.75	22.0	24.55	1.83	0.94	1.48	0.5
0.56	13.4	3000	5.5	44.0	49.1	3.65	1.9	2.95	0.98
0.84	20.2	5000	8.25	66.0	73.65	5.47	2.83	4.3	1.43
1.12	26.9	4000	11.0	88.0	98.2	7.29	3.8	5.9	1.97
1.4	33.6	5000	13.75	110.0	122.75	9.12	4.72	7.4	2.5
2.8	67.2	10,000	27.5	220.0	245.5	13.24	9.44	14.76	4.92
3.2	76.8	15,000	41.25	330.0	368.25	20.8	10.8	16.9	5.62
5.6	134.4	20,000	55.0	440.0	491.0	36.48	18.9	29.52	9.84
7.0	168	25,000	68.75	550.0	613.75	45.6	23.6	36.9	12.3

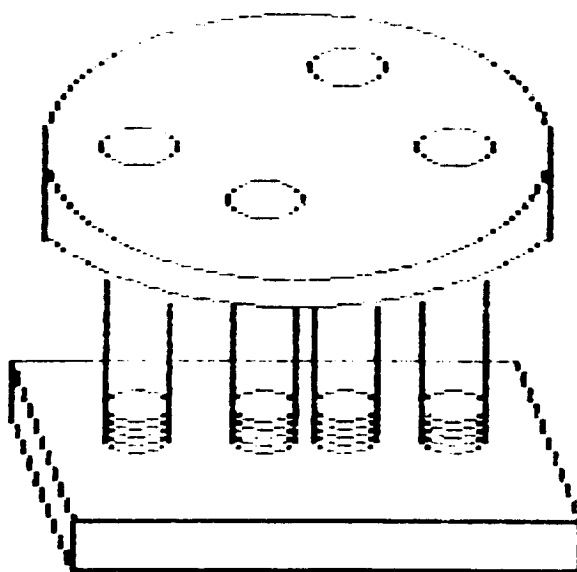
Table 4.2

# **SIMPLE FUEL CELL REGULATORS**

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**(b) Rotating Disc**



**(a) Series Connected**

**Figure 4.30**

partial and full power. Furthermore, the efficiency is independent of its size. Fuel cells are quiet, clean (low emissions), and produce potable water while in operation that can be used for system cooling, drinking, or elevator balance. Fuel cell power plants are inherently modular down to the level of the individual cell, which can allow for reconfiguration to virtually any size. The relatively small weight and volume of the total system can produce large energy outputs, and are durable and reliable.

#### Chapter 49. STORAGE/BACKUP STRATEGIES

A storage/backup system must be implemented on the TES in order to provide redundancy in the event of primary system failure. The storage/backup system must be capable of, at a minimum, retrieving the TES from any point along the tether. This can be accomplished in one of the two ways; batteries or an alternate fuel cell.

Nickel-Hydrogen batteries were optimized in Design Phase I. Ni-H<sub>2</sub> batteries are rechargeable and highly reliable. They can provide three times the energy density (energy stored per unit weight) and five times the lifetime of traditional Nickel-Cadmium batteries. According to standard battery sizing formulas, a twenty-one cell battery with a rated capacity of 50 amp-hours per cell will be required to meet the elevator needs. These cells will be interconnected in series which will allow them to be easily configured to fit in a confined space on the elevator. The total battery mass will only be 31.9 kilograms which adds very little to the overall TES.

A fuel cell power plant would also prove to be a viable backup system. In the event of a primary power source failure the backup fuel cell could provide the power necessary to salvage any essential mission requirements. Fuel cells are currently used as a backup system for electrical energy on the Space Shuttle Orbiter.[57]

#### Chapter 50. POWER TRANSMISSION SYSTEM

In conjunction with the search for the appropriate power supply for the TES research was conducted as to the best method of power transmission to all elevator components. PMG's and microwaves were given considerable study. However, due to the optimization of fuel cells as the primary power source and their location aboard the elevator, the relatively short distance between the drive motors, robotic arms and power supply necessitated the consideration of coaxial cable. The coaxial cable is similar to that used in television or telephone transmission. It offers an extremely inexpensive,

safe and reliable method of transmitting power which effectively minimizes environmental and drag effects. Coaxial cable also offers the most simple design and was easily optimized.

## Chapter 51. SOLUTION OPTIMIZATION - PHASE II

Power generation systems in space must have certain qualities. The three specific sources (electrodynamics, photovoltaics, and fuel cells) all possess these qualities. However, one particular design proved to be more acceptable for the TES application. This design was to use fuel cells to convert chemical energy to electrical energy.

Fuel cells offer the most attractive power source for the TES, given the present technology. Their many proven space applications range from use on the Apollo and Gemini spacecraft to the Space Shuttle Orbiter. Their reliability and technical feasibility were among the major factors considered in arriving at this decision. The conversion of electrochemical energy into electricity by fuel cells is extremely efficient, since they are not limited to the Carnot engine cycle.

Due to the small size and modularity of fuel cells, they can be attractively configured to meet virtually any power requirement without sacrificing efficiency. Fuel cells would also allow for future reconfiguration to meet increased loads as needed. Fuel cell power is relatively continuous in nature since their oxygen and hydrogen tanks can be refueled. Lastly, fuel cells produce no noxious emissions and very little noise which is essential for a proper experimental habitat.

The storage/backup is necessary to provide some amount of redundancy in the TES's power supply. Ni-H<sub>2</sub> batteries were the optimal solution of Phase I.[59] They were chosen over the Ni-Cd batteries due to their higher watts-to-kilogram output ratio. Another form of redundancy would be the use of a secondary fuel cell. This fuel cell would take over in case of primary fuel cell failure.

The optimal solution, for this application was found to be the use of both systems. A secondary fuel cell will be the primary backup system. The fuel from the primary fuel cell will be rechanneled to the secondary fuel cell through a series of regulator valves in case of primary fuel cell failure. In the case of regulator valve failure the secondary fuel cell will also be equipped with two emergency fuel tanks capable of retrieving the TES from any point on the tether. Each tank will be equivalent in size to those of the primary fuel cell and capable of 56 hours of continuous

operation. Ni-H<sub>2</sub> batteries will be used in the unlikely event of total failure of both primary and secondary fuel cell systems.

In summary, a fuel cell will be used as the primary power source. Storage/backup will be in two stages. Firstly, a secondary fuel cell to provide total functionality and/or return to SS and secondly a Ni-H<sub>2</sub> battery pack capable of retrieving the elevator from any point on the tether. It has been determined that coaxial cable will be used to transmit the power to the drive and robotics mechanisms due to their short distance from the power source. The basic configuration of the power and storage/backup system is shown in Figure 4.31. i

## OPTIMAL POWER SYSTEM

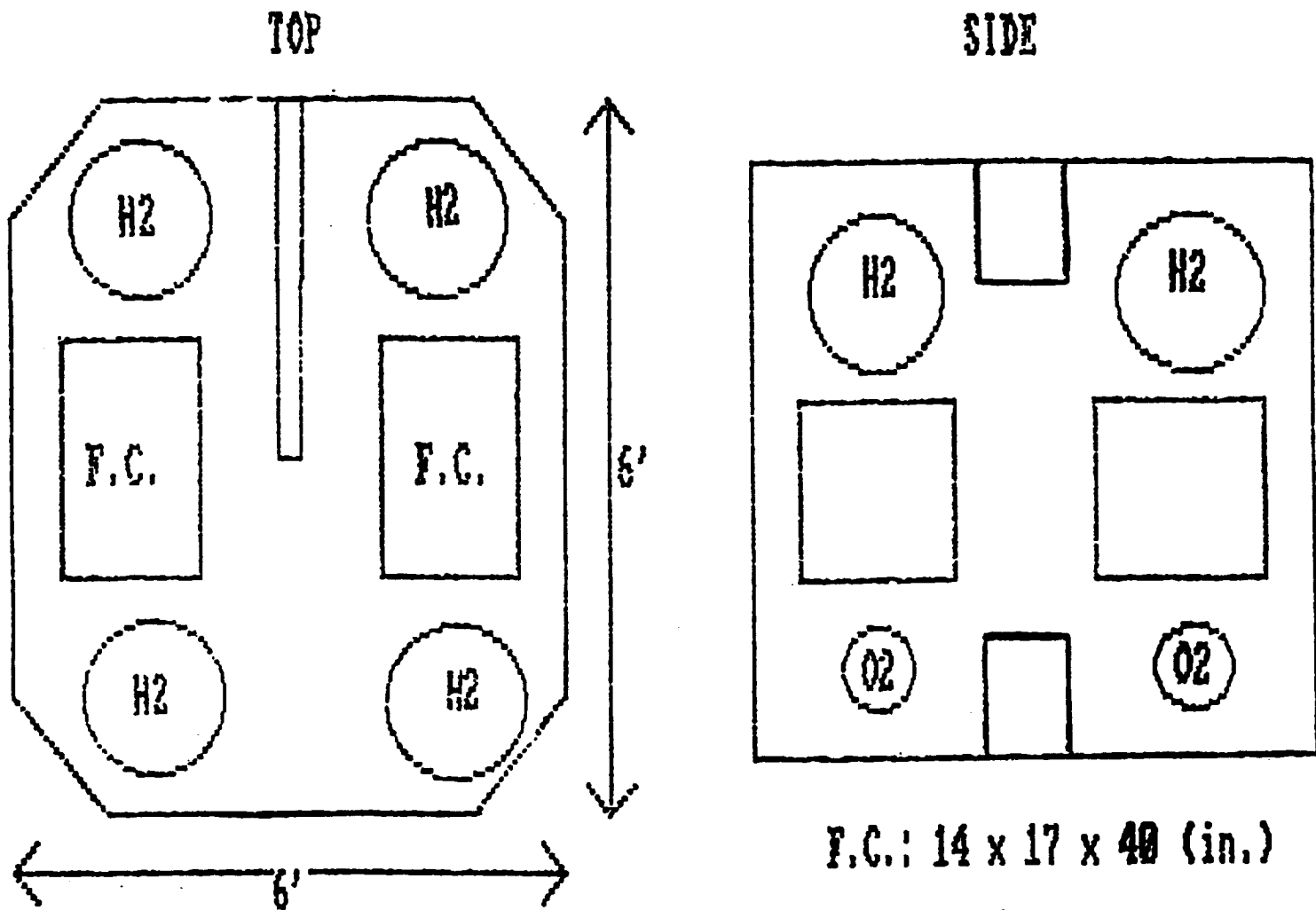


Figure 4.31

SECTION V.

TETHERED ELEVATOR SYSTEM OPERATION



## Section V. TETHERED ELEVATOR SYSTEM OPERATION

The purpose of this section is to describe the sequence of events and associated operational characteristics of the tethered elevator on a typical mission in low Earth orbit.

The first step in initiating an elevator mission is to attach the vehicle to a tether extended from the Space Station. At the time of mission commencement, the elevator will be retrieved from a servicing bay or hangar located on the Space Station. Station robotics will grasp a standard grapple fixture centrally located on the elevator housing. The elevator will then be manipulated, with attached payloads, toward the extended tether. At this point, commands will be sent to the elevator to place the linear actuators and capture mechanisms of each driver in their open configurations. The elevator will then be positioned onto the tether. During this event, the tether is effectively funnelled into the stationary guide slot and positioned for capture. Remote optics next verify the tether is properly aligned and the capture disks are commanded to rotate ninety degrees. Finally, the linear actuators are activated and pressure blocks are forced to close around the tether. This completes the elevator hooking procedure.

Subsequent to elevator/tether mate, the vehicle must accelerate, attain a constant velocity, and decelerate as not to incur unwanted disturbances in the tether or on the Station. The vehicle is next "powered up" and operating self-sufficiently before displacement of the elevator occurs. When full power of seven kilowatts is realized, first motion of the vehicle is initiated. During traversal, data from the drive mechanisms and control sensors will be monitored by computers on the Station. As the elevator approaches its destination, the drive motors will shut down and regenerative motors will be engaged to brake the elevator smoothly.

When the elevator reaches its destination, the robotic arms, controlled by an IBM AP-101 computer, will be maneuvered to perform various tasks. Elevator-based experiments and mission duties will take place at this time. After tasks are complete, the elevator will return to the Station under the aforementioned seven kilowatts of power provided continuously by fuel cells.

At the time the elevator reaches its point of origination, it will once again be grasped by a Station-based manipulator and be detached from the tether. Fuel cells will be replenished and payloads will be reconfigured for the next mission of the Space Station tethered elevator.

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## APPENDIX A

## APPENDIX A

### DYNAMIC ANALYSIS

#### Table of Values and Nomenclature

FC	= Centrifugal Force (N)	
FG	= Gravitational Force (N)	
T	= Tension Force in the Tether (N)	
W	= Angular Velocity of Space Station and End mass system (rad/s)	
A(t)	= Acceleration at time t	
V(t)	= Velocity at time t	
X(t)	= Position at time t	
t	= time (s)	
R3	= Radius of the elevator (m)	
Ac	= Coriolis acceleration (m/s <sup>2</sup> )	
Fc	= Coriolis force (N)	
XC.G.	= Center of gravity (m)	
L	= Length of the tether (m)	10,000 m
Me	= Mass of the earth (m)	$5.979 \times 10^{24}$ kg
M1	= Mass of the Space Station (kg)	250,000 kg
M2	= Mass of the Tethered end mass (kg)	50,000 kg
meu	= Mass of the Elevator unloaded (kg)	5,000 kg
mel	= Mass of the Elevator Loaded (kg)	25,000 kg
R1	= Radius of the Space Station orbit (m)	$6.69 \times 10^6$ m
R2	= Radius of the end mass orbit (m)	$6.68 \times 10^6$ m

#### Approach

For the following analysis certain assumptions have been made and are stated throughout the text. Other assumptions not stated are as follows: the orbit of the system is considered to be circular, the origin is considered to be where the tether attaches to the SS unless otherwise stated, and that a 10km tether is considered to be short. With the assumption of a short tether, the tether mass can be neglected. These assumptions will aid in tether tension calculations since tether tension is mainly dictated by gravitational forces. Finally, all radii are assumed to be displacement distances from the center of the earth.

#### Center of Gravity Movement

The center of gravity of the SS/end mass system is of considerable importance. Without the end mass it is not possible to tap the microgravity gradient. As the elevator traverses down the tether from the SS, the CG moves farther away from the SS. When the elevator is located at the CG, the distance from the SS to the CG is the same as if the elevator was not attached to the tether. At this point the elevator's



centrifugal force balances its gravitational force and the elevator CG is coincident with the system CG. Using the equations below the center of gravity as a function of elevator position can be calculated for any desired position.

$$XC.G. = \frac{(M1R1 + M2R2 + me1R3)}{(M1 + M2 + me1)}$$

Figure A1 is a plot of the center of gravity verses elevator position as the elevator travels from the space station to the end mass.

### Tether Tension Analysis

<u>Space Station</u>	<u>End mass</u>
FG1 = (MeGM1)/R1^2	FG2 = (MeGM2)/R2^2
FC1 = M1R1W^2	FC2 = M2R2W^2
T1 = FC1 - FG2	(SS system)
T2 = FG2 - FC2	(End mass system)

The equations listed above are for the centrifugal force and the gravitational force for the space station and the end mass. These are the only forces acting on the system neglecting any drag effects. By cutting the tether and summing the forces acting on the SS or the end mass, the tension equations listed above can be created. These two tension forces are equal in magnitude and opposite in direction. However, before these equations can be solved, the angular velocity of the system must be determined. By setting T1 = T2 the equation below can be developed to determine the systems angular velocity.

$$W = \frac{[(MG) ((M1/R1^2) + (M2/R2^2)) ]^{.5}}{[(M1R1 + M2R2)]^{.5}}$$

The angular velocity has been calculated for the three different cases listed below. For these calculations, the mass of the elevator has been used as 25,000 kg which is fully loaded.

1. No elevator mass on system.
2. The elevator mass at the end mass.
3. The elevator mass at the space station.

For each of these cases listed, the angular velocity has been carried out to the 15th decimal place for accuracy; since the difference in magnitude for the above three cases is not noticed until the 6th decimal place. This is also

# CENTER OF GRAVITY vs. ELEVATOR POSITION

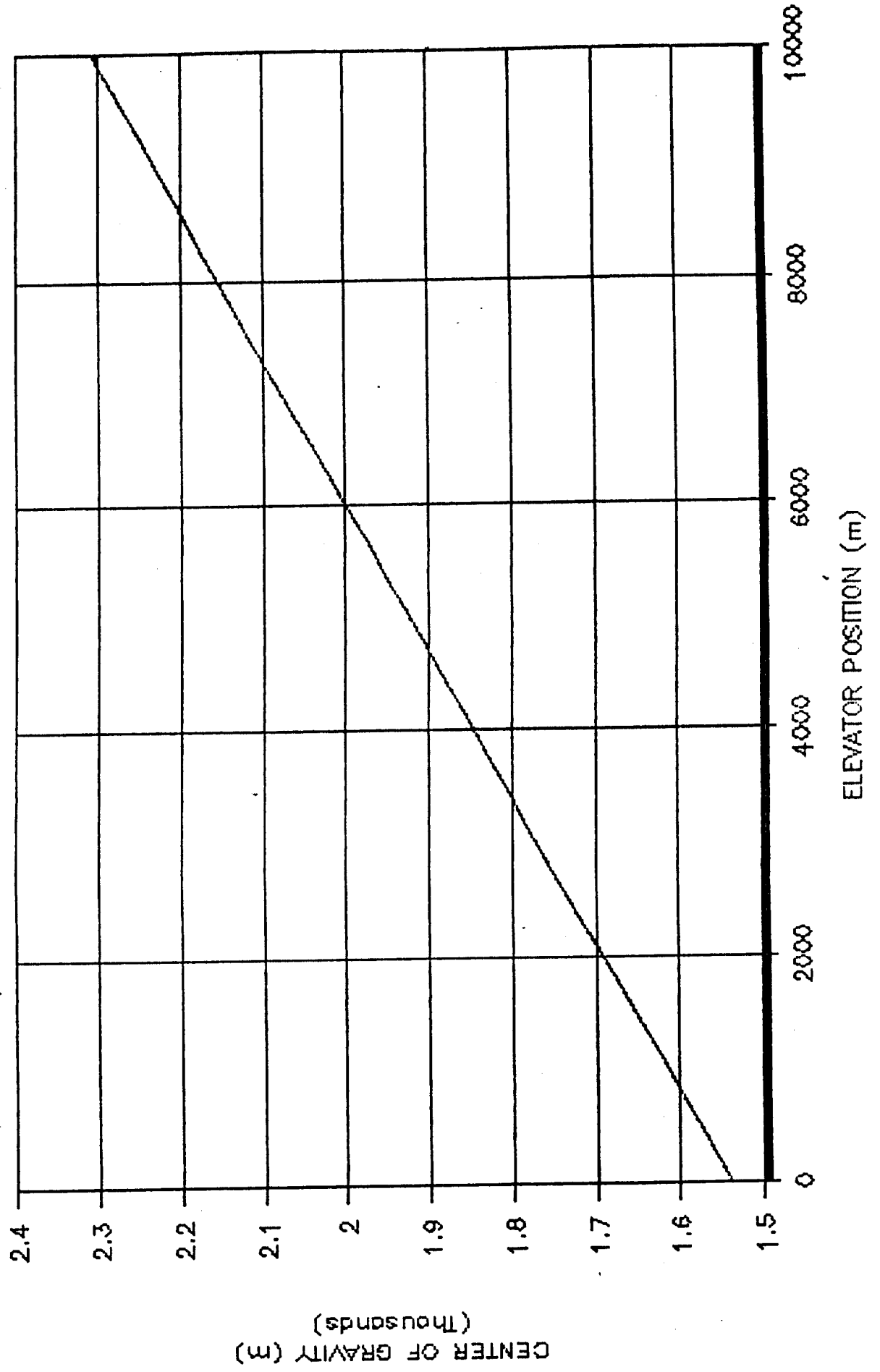


Figure A1

necessary for accuracy in the calculations. When the angular velocity is substituted into either tension equation, the tension for all three cases can be calculated.

<u>CASE</u>	<u>ANGULAR VELOCITY (rad/sec.)</u>	<u>TENSION (N)</u>
1.	W = .00115493323550	T = 1669
2.	W = .00115493323550	T = 2310
3.	W = .00115475390312	T = 1694

### Maximum Allowable Acceleration

It is necessary to calculate the maximum allowable acceleration of the elevator in order to determine if any longitudinal vibrations are induced along the tether. These longitudinal vibrations would arise when the driver force exceeds the tether tension and would then cause slack in the tether. By setting the equation below equal to the tension in the tether with the elevator fully loaded the maximum acceleration of the elevator can be determined. Again for the three cases stated earlier we have calculated the acceleration.

$$F = m_{el} * A_{max}.$$

<u>CASE</u>	<u>MAXIMUM ALLOWABLE ACCELERATION (m/s<sup>2</sup>)</u>
1.	A <sub>max</sub> . = .3338
2.	A <sub>max</sub> . = .0924
3.	A <sub>max</sub> . = .06776

From the results above the worst case would be when the elevator is fully loaded at the space station. From the above calculation the acceleration needs to be limited to less than .06776 m/s<sup>2</sup> so as not to induce longitudinal vibrations. This value will also be used for the deceleration calculations in the rest of this analysis.

### Time to Accelerate/Decelerate

The velocity of the elevator has been limited to 2 m/s to conserve power and to reduce the Coriolis acceleration. Since the acceleration and deceleration values are the same magnitude, but in opposite direction, the deceleration time will be a mirror image of the acceleration time. With the use of this data, the time of the elevator to accelerate and decelerate will be calculated.

$$2 \text{ m/s} = (.06776 \text{ m/s}^2)t$$

$$t = 29.5 \text{ sec.}$$

## Acceleration, Velocity, and Position Profile

From the above acceleration data and the other known constants, the acceleration, velocity, and position equations will be determined and plotted to achieve an estimate of the performance of the elevator. For the equations below the acceleration value of .06776 m/s<sup>2</sup> is used as an instantaneous value with no lag time. Also the maximum velocity of the elevator is used. The equations below are split into three sections because of the changing acceleration. The origin for  $t = 0$  and  $X = 0$  is considered to be at the space station.

For ( $t = 0 - 29.5$  sec.) and ( $X = 0 - 29.5$  m):

$$\begin{aligned}A(t) &= [.06776] \text{ m/s}^2 \\V(t) &= [(.06776)t] \text{ m/s} \\X(t) &= [(1/2)(.06776)t^2] \text{ m}\end{aligned}$$

For ( $t = 29.5 - 5000$  sec.) and ( $X = 29.5 - 9970.5$  m):

$$\begin{aligned}A(t) &= [0] \text{ m/s}^2 \\V(t) &= [2] \text{ m/s} \\X(t) &= [2(t-29.5) + 29.5] \text{ m}\end{aligned}$$

For ( $t = 5000 - 5029.5$  sec.) and ( $X = 9970.5 - 10,000$  m):

$$\begin{aligned}A(t) &= -.06776 \text{ m/s}^2 \\V(t) &= [(-.06776)(t-5000) + 2] \text{ m/s} \\X(t) &= [(1/2)(-.06776)(t-5000)^2 + 2t + 9970.5] \text{ m}\end{aligned}$$

From the governing equations listed above, it has been determined that the total time for the elevator to traverse the tether from the space station to the end mass is 5029.5 sec. or 1.4 hrs.

Plots have been supplied for acceleration, velocity, and time (Figures A2-A4). For the acceleration and the velocity the time limit on the X-axis has been limited to 100 sec. for clarity during the acceleration part of the curve. It should also be noted that for the acceleration curve it is equal in magnitude and opposite in direction for the time period 5000 - 5029.5 sec. For the velocity curve it is a constant value of 2 m/s for the time period 100 - 5000 sec. and is a mirror image of the initial part of the curve (0 - 29.5 sec.) for the time period 5000 - 5029.5 sec.

## Coriolis

The Coriolis force is directly proportional to the relative velocity of the elevator. Therefore, by limiting the velocity of the elevator, the Coriolis force will be limited. Calculated below are the Coriolis acceleration and

# ACCELERATION vs. TIME

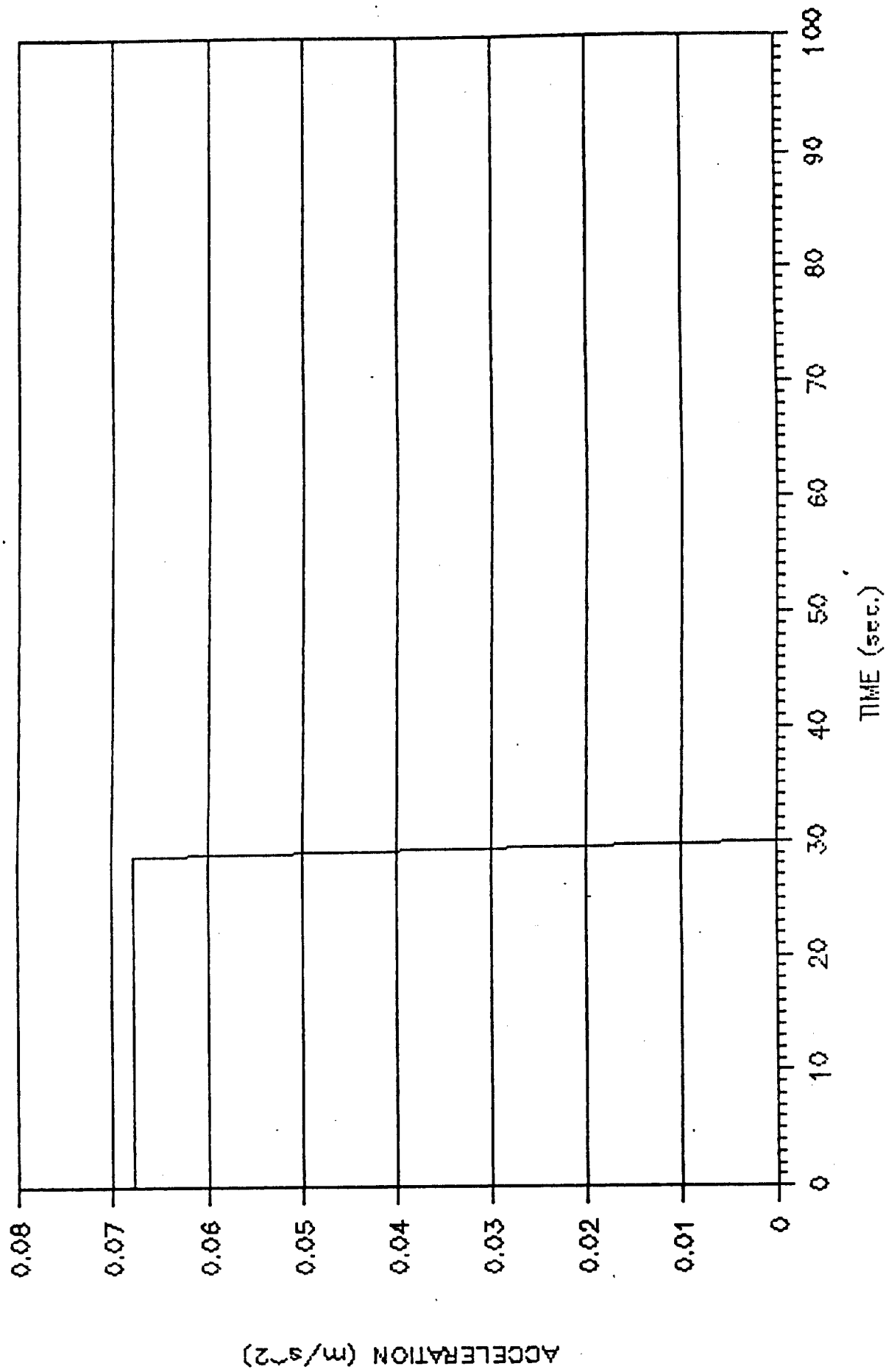


Figure A2

# VELOCITY vs. TIME

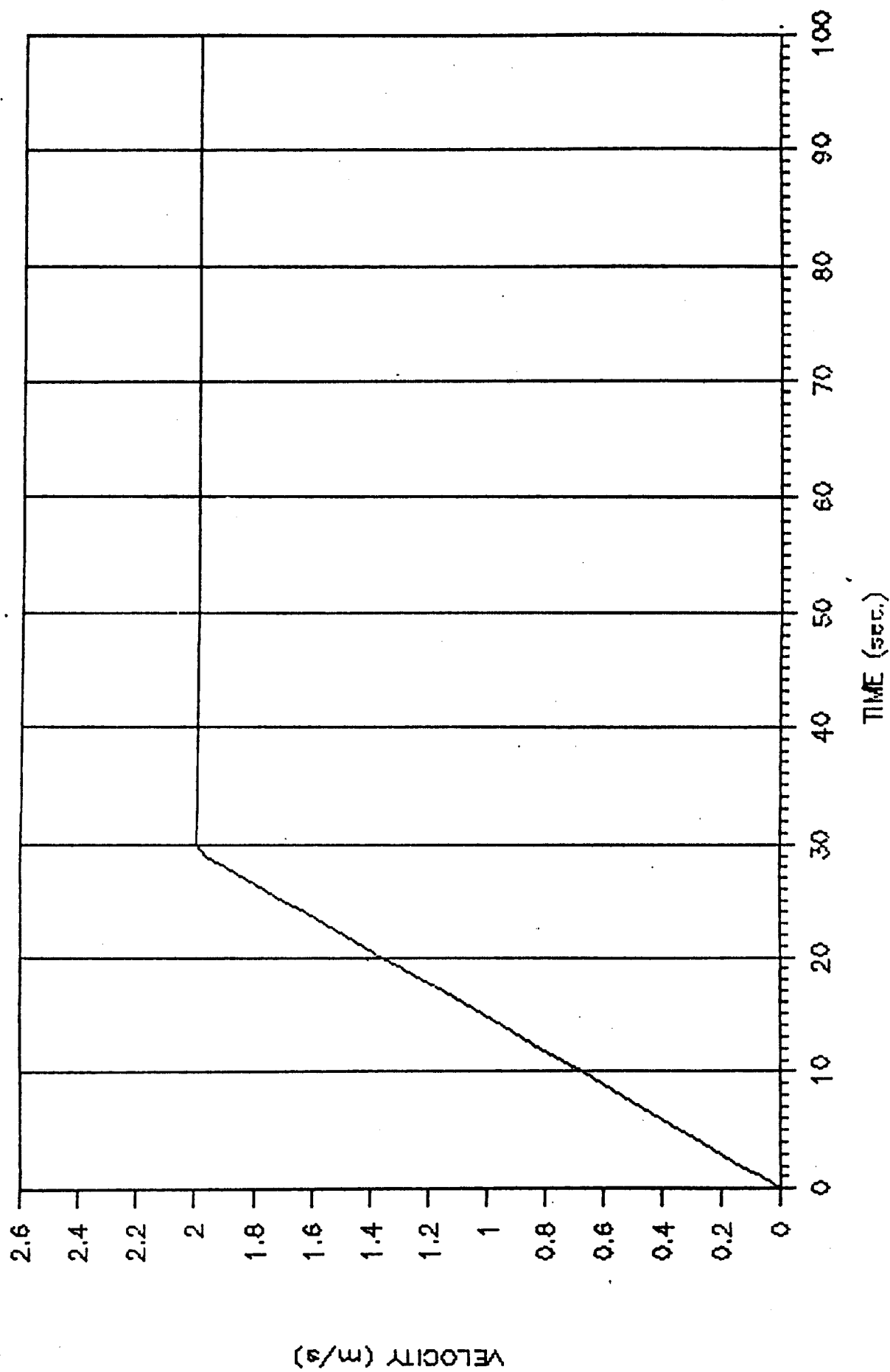


Figure A3

# ELEVATOR POSITION vs. TIME

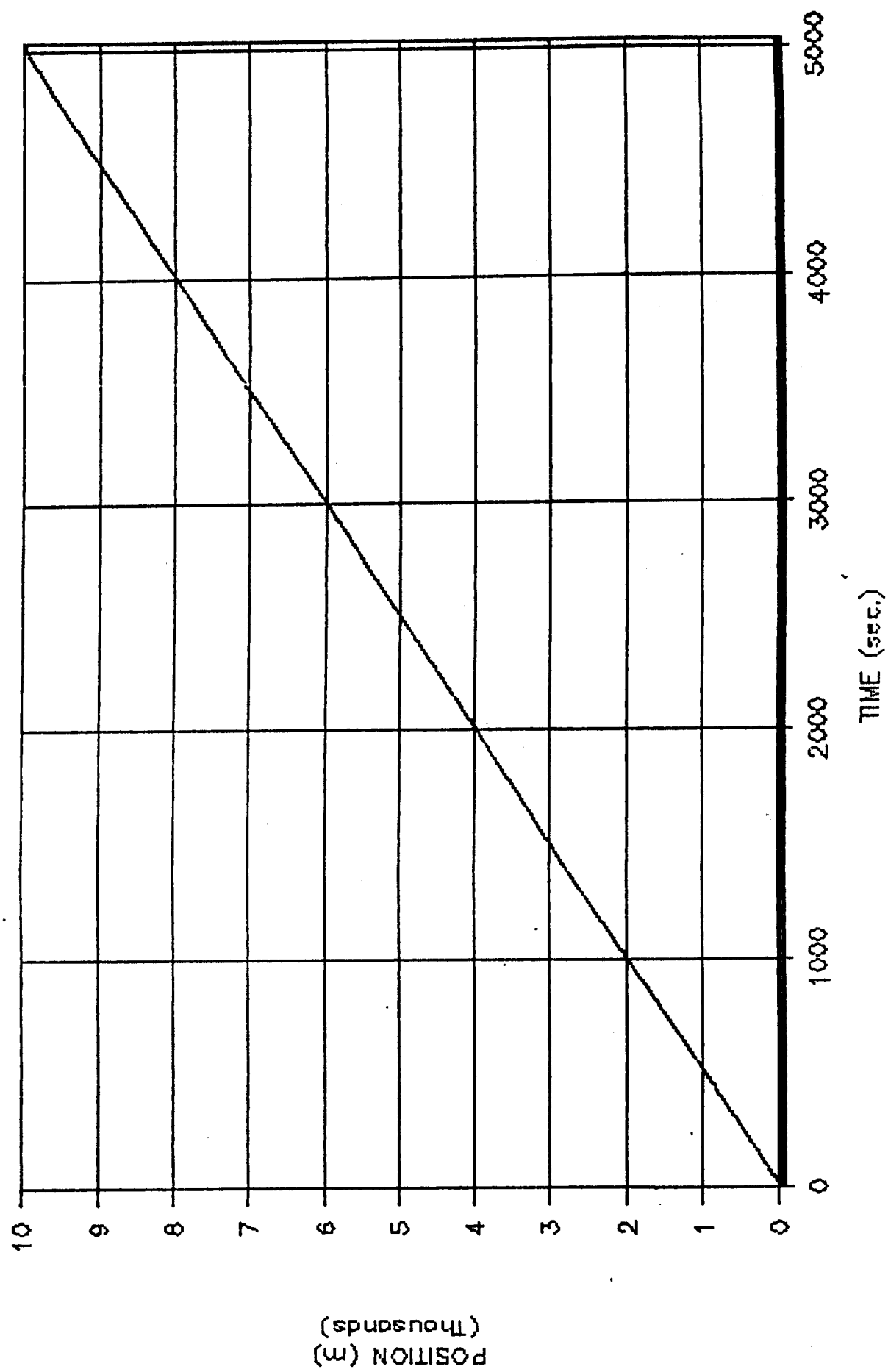


Figure A4

the Coriolis force. Note that the Coriolis force can vary due to the elevator being loaded or unloaded.

$$\begin{aligned} A_c &= (2*W) \times V && \text{Coriolis Acceleration} \\ &= 2*(.00115474390312 \text{ rads/sec})*(2 \text{ m/s}) \\ &= .004619 \text{ m/s}^2 \end{aligned}$$

$$\begin{aligned} F_c &= m*A_c && \text{Coriolis Force} \\ &= (5000 \text{ kg})*(.004619 \text{ m/s}^2) \\ &= 23.1 \text{ N} && \text{(Elevator unloaded)} \\ &= (25000 \text{ kg})*(.004619 \text{ m/s}^2) \\ &= 115.5 \text{ N} && \text{(Elevator Max. Load)} \end{aligned}$$

The direction of the Coriolis force is perpendicular to the relative velocity of the elevator on the tether. This is easily seen by using the right hand rule on the Coriolis acceleration equation above.

#### Tether Angle Analysis

The tether angle is created by the Coriolis force. This force will rotate the space station end mass system about its center of gravity and create an angle with respect to its original position. For the worst case possible Coriolis force the 115.5 N will be used when the elevator is fully loaded and moving at 2 m/s. The angle can have different magnitudes depending on the position of the elevator.

1. Elevator 29.5 m from the SS.
2. Elevator 29.5 m from the end mass

The tension in the tether is a known value, the Coriolis force is of known value and direction, and the other component is of known direction. This angle can be calculated by drawing force triangles for both cases and calculating the angle with respect to the vertical. For each of the cases the angles are calculated when the elevator is below the SS or the end mass by 29.5 m since this is the point where the maximum velocity is achieved.

Due to the rotation of the system about the C.G. the end mass is displaced from its nominal position. Since the C.G. is closer to the SS, the end mass will have the greatest displacement when the coriolis force is induced. Shown below are tether angles and displacement values for the end mass.

<u>CASE</u>	<u>CENTER OF GRAVITY</u>	<u>TETHER ANGLE</u>	<u>DISPLACEMENT</u>
1.	1540 m	3.97 deg.	583 m
2.	2305 m	2.87 deg.	383 m



APPENDIX B

ORIGINAL PAGE IS  
OF POOR QUALITY

### \* Optimal Solution

## Matrix 1.1

# MAIN UNIT SHAPES

Weight Factors	DESIGN PARAMETERS										STRESS AREAS							TOTALS	
	Simplicity	External Storage	Internal Storage	Mass	Maintainability	EVA	EVA	Transportability	Robotics Location	Payload Interface	Structural Stability	CM Adjustment	Feasibility	Cost	Durability	Shielding	Compatibility w/ Systems		
SQUARE	18	16	18	14	17	17	16	15	16	18	14	15	18	18	15	15	17	15	2056
RECTANGLE	17	15	16	16	16	17	16	15	15	17	15	16	18	17	14	15	15	15	2105
*OCTAGON	14	16	17	16	17	18	17	17	17	17	17	16	17	15	17	15	18	18	2234 *
PENTAGON	15	14	15	15	17	17	17	16	16	14	16	15	16	16	16	16	16	17	2138
WEDGE	12	14	14	15	15	15	16	18	13	15	13	14	15	12	15	15	13	16	1849

\* Optimal Solution

# POSITIONING GEOMETRIES

Weight Factors	DESIGN PARAMETERS															TOTALS	
	9	8	7	7	6	8	8	8	9	7	6	10	7	8	9		
HOLLOW SQUARE	19	18	18	18	18	18	18	18	19	18	18	19	2	18	13	15	1918
STATIONARY SLOT	18	18	17	18	18	19	17	18	12	17	18	18	17	19	19	2058 *	
SLIDING SLOT	16	15	15	17	15	16	15	16	17	15	16	18	16	16	17	1861	
CROSSING SLOTS	17	17	17	18	18	17	14	18	13	17	17	17	17	18	18	1957	
ROTATING SLOT	15	16	16	16	16	18	17	17	19	16	15	19	17	19	17	1970	

# POSITIONING MECHANISMS

DESIGN PARAMETERS	WEIGHT FACTORS																	TOTALS		
	8	7	8	5	7	8	7	9	8	7	10	6	7	8	7	6	6			
Simplicity	17	16	17	17	17	17	17	16	13	15	18	17	18	18	14	16	17	2043		
Durability	15	16	16	15	15	16	17	15	18	17	17	17	16	17	17	18	16	2028		
Disturbance	14	14	15	16	14	15	18	17	16	15	16	16	15	15	15	15	16	1912		
Required Storage Volume	18	17	17	18	17	17	16	16	17	18	15	19	17	18	18	17	17	2119 *		
Mass																				
Maintainability																				
EVA/IVA																				
Hook/Unhook																				
Performance																				
Reliability																				
CM Adjustment																				
Feasibility																				
Cost																				
Load Capacity																				
Vibration																				
Stability																				
Power Requirement																				

\* Optimal Solution

# COUNTERBALANCE MECHANISMS

DESIGN PARAMETERS	Weight Factors																	TOTALS
	8	8	7	7	6	9	8	7	10	8	7	7	6	9	7	7	7	
*TELESCOPING STRUT	19	18	18	17	16	18	18	17	18	17	16	17	16	17	17	17	17	2096*
SCISSORS MECH	15	14	15	13	15	19	16	15	16	15	14	13	18	14	15	16	16	1852
WORM GEAR	17	17	17	18	16	14	17	18	17	18	18	18	15	18	16	18	18	2057

\* Optimal Solution

# ELEVATOR DESIGN

DESIGN PARAMETERS	WEIGHT FACTORS																TOTALS	
	9	7	7	8	6	8	6	7	6	8	6	6	7	6	7	7	6	
SIMPLICITY	17	17	18	17	16	17	17	16	17	18	18	18	17	19	18	17	16	2364 *
DURABILITY	16	17	16	17	16	16	16	16	16	17	17	16	16	17	18	17	15	2262
INTERNAL STORAGE	17	15	15	17	17	16	16	16	16	17	16	17	16	15	15	15	17	2222
MASS																		
MAINTAINABILITY																		
ACCESSIBILITY																		
EVA/IVA																		
HOOK/UNHOOK																		
PERFORMANCE																		
TRANSPORTABILITY																		
ROBOTICS																		
RELIABILITY																		
PAYLOAD CAPACITY																		
STABILITY																		
CM ADJUSTMENT																		
POWER																		
FEASIBILITY																		
COST																		
SHIELDING																		

\* Optimal Solution

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WEIGHTED TOTAL														
ENERGY REQUIREMENTS														
CONFORMANCE RISK														
FLEXIBILITY														
SIMPLICITY														
DURABILITY														
RELIABILITY														
MAINTAINABILITY														
OPERATIONAL PERFORMANCE														
HUMAN INTERFACE														
EVA														
INITIAL COST														
SAFETY														
WEIGHTED FACTOR ( 1 - 5 )	5	2	4	5	5	3	4	3	4	4	1	2	3	2
FIXED MOUNT	20	17	17	16	7	20	13	20	19	4	19	19	18	20
QUICK REMOVE	17	10	14	13	12	14	12	18	15	11	17	15	15	17
TRACK DRIVE	12	12	7	7	19	5	6	9	7	9	10	8	7	11
MULTIPIN CONNECTION	15	15	11	11	16	12	15	17	18	12	20	15	19	13
COAXIAL CONE CONNECTOR	5	8	18	18	11	12	8	14	14	12	20	11	19	13
56														
49														

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20  
POOR EXCELLENT

ELEVATOR INTERFACE PERFORMANCE MATRIX



WEIGHTED TOTAL
INTERFACIAL
MENT

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# END EFFECTOR PERFORMANCE MATRIX

	SAFETY	INITIAL COST	OPERATIONAL COST	EVA	HA	HUMAN INTERFACE	MAINTAINABILITY	RELIABILITY	DURABILITY	SWAPABILITY	TECHNICAL AVAILABILITY	TIME REQUIRED ON ELEVATOR	CONTAMINATION RISK	SIZE	MASS	ENERGY REQUIREMENT	DEXTERITY	WEIGHTED TOTAL	
WEIGHTED FACTOR ( 1 - 5 )	5	2	3	4	1	5	5	3	4	3	4	5	1	3	1	2	3	2	4
ONE ARM TOOL	16	15	14	11	16	15	8	14	16	13	17	4	17	12	18	14	15	15	4
TWO ARM TOOL	15	10	13	12	17	17	12	13	14	13	15	11	14	10	16	17	12	13	11
THREE ARM TOOL	13	7	8	11	12	7	15	11	12	13	11	16	9	7	15	17	10	11	9
FOUR ARM TOOL	11	3	7	12	8	7	16	9	10	12	12	19	7	5	14	16	8	9	19

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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20  
POOR EXCELLENT

# ARM END EFFECTOR TOOL PERFORMANCE MATRIX

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	SAFETY	INITIAL COST	EVA	VA	HUMAN INTERFACE	OPERATIONAL PERFORMANCE	RELIABILITY	DURABILITY	SIMPLICITY	FLEXIBILITY	TECHNICAL AVAILABILITY	STORAGE ON ELEVATOR	TIME REQUIRED STARTUP	CONTAMINATION RISK	MASS	ENERGY REQUIREMENT	DEXTERITY	WEIGHTED TOTAL		
WEIGHTED FACTOR ( 1 - 5 )	5	2	4	1	5	5	3	4	4	5	1	3	3	1	2	3	2	4		
JPL GRIPPER	14	8	12	13	13	13	9	15	17	10	15	13	15	15	14	16	14	11	15	
LANGLEY INTELLIGENT END EFFECTOR	16	6	13	12	13	13	10	15	16	10	11	11	9	15	15	16	13	12	11	
JPL PROTOTYPE	13	7	9	10	12	12	8	14	15	11	10	14	15	15	13	14	13	11	10	
VERSA GRIP III	16	7	13	9	9	10	7	13	13	12	9	15	15	15	12	14	12	11	9	
3 FINGER MULTI JOINT	16	4	10	12	12	16	6	11	8	7	17	10	8	13	14	13	15	12	11	17
3 MULTI JOINT FINGER	14	5	10	12	14	15	6	11	8	6	18	10	8	13	14	13	15	12	11	18
4 FINGER	15	3	10	13	18	17	8	9	6	3	19	4	8	12	15	12	17	10	9	19
MULTI JOINTED FINGER	14	5	10	15	18	17	9	11	5	4	19	4	8	12	15	12	17	11	9	19
MAGNETIC GRAPPLE	18	10	9	16	16	9	18	18	19	16	6	17	16	15	13	11	11	12	2	6

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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20  
POOR EXCELLENT

CRIPPER END EFFECTOR TOOL PERFORMANCE MATRIX

ORIGINAL OF

WEIGHTED TOTAL

SECURITY REQUIREMENT

	SAFETY	INITIAL COST	EVA	N/A	HUMAN INTERFACE	OPERATIONAL PERFORMANCE	RELIABILITY	DURABILITY	SIMPLICITY	FLEXIBILITY	MECHANICAL AVAILABILITY	STORAGE IN SPACE	TIME REQUIRED STARTUP	SIZE	MASS	ENERGY REQUIREMENT	DEXTERITY	WEIGHTED TOTAL		
WEIGHTED FACTOR ( 1 - 5 )	5	2	3	4	1	5	3	4	3	4	5	1	3	2	3	2	4			
TELEOPERATIONS	14	14	5	10	8	14	14	11	13	15	14	9	16	0	13	7	15	16	15	6
TELEROBOTICS	10	9	4	15	14	10	15	12	13	11	9	12	12	1	13	15	13	12	12	14
AUTONOMOUS	5	4	3	15	15	5	15	12	11	6	2	16	2	1	11	14	11	9	9	16

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20  
POOR EXCELLENT

# CONTROL SYSTEM PERFORMANCE MATRIX

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WEIGHTED FACTOR ( 1 - 5 )	INITIAL COST										WEIGHTED TOTAL									
	SAFETY	HUMAN INTERFACE	MAINTAINABILITY	RELIABILITY	DURABILITY	SIMPLICITY	FLEXIBILITY	TECHNICAL AVAILABILITY	SPACE IN SPACE STATION	SPACE STATION DISTURBANCE	TIME REQUIRED STARTUP	MASS	ENERGY REQUIREMENT	DEXTERITY						
JOYSTICK	5	2	1	5	5	3	4	3	4	4	5	3	1	3	2	3	2	4	47	
MASTER SLAVE	20	16	10	12	9	15	15	19	19	7	19	18	1	12	15	18	17	9	35	
EXOSKELETAL	17	12	7	15	3	12	15	17	15	8	17	3	1	15	2	5	14	7	40	
HELMET	18	13	12	19	11	6	11	11	9	14	9	13	1	19	11	13	15	16	39	
	18	9	15	19	7	12	11	11	9	7	10	13	1	19	13	16	15	10		

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20  
POOR EXCELLENT

# MAN MACHINE INTERFACE PERFORMANCE MATRIX

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	SAFETY	INITIAL COST	OPERATIONAL COST	HUMAN INTERFACE	MAINTAINABILITY	RELIABILITY	DURABILITY	SMPLXITY	FLEXIBILITY	STORAGE IN SPACE	CONTAMINATION RISK	SIZE	MASS	ENERGY REQUIREMENT	DEXTERITY	WEIGHTED TOTAL
WEIGHTED FACTOR ( 1 - 5 )	5	2	3	5	5	3	4	4	5	3	1	2	3	2	4	
ELECTROMECHANICAL	16	15	3	0	11	5	6	11	8	19	5	11	11	5	11	49
DIGITAL SERVO MANIPULATOR	18	8	3	0	18	5	6	12	11	19	8	14	16	14	6	58

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20  
POOR EXCELLENT

# DRIVE MOTOR PERFORMANCE MATRIX

# COMPUTER HARDWARE SYSTEMS

WEIGHT FACTORS	9	7	6	5	8	4	10	10	8	3	8	TOTALS
DESIGN PARAMETERS												
PHYSICAL DIMENSIONS												
INTERFACING												
STORAGE CAPACITY												
POWER CONSUMPTION												
SOFTWARE ADAPTABILITY												
EASE OF OPERATION												
EFFICIENCY												
RELIABILITY												
SERVICING												
VERSATILITY												
NORTHNESS												
DECVAX II	11	18	17	15	17	17	18	17	14	16	10	1026
MOTOROLA 68000	9	18	17	15	17	17	18	16	15	17	10	993
IBW AP-101	18	18	16	15	15	18	18	18	17	18	19	1232 **

\*\* Optimal Solution

# DATA COMMUNICATIONS LINK

WEIGHT FACTORS	7	7	5	8	8	6	9	7	9	4	8	TOTALS
PACKET RADIO	16	17	14	18	15	15	19	15	19	20	20	1342 **
LASER	10	19	14	19	16	10	19	15	19	17	19	1199
FIBER OPTICS	12	14	12	14	11	12	19	15	19	15	8	1049
ELECT./COAX.	13	12	10	10	10	17	19	15	19	10	8	957

\*\* Optimal Solution



# FORCE / TORQUE SENSORS

WEIGHT FACTORS	DESIGN PARAMETERS								OPERATIONAL PERFORMANCE				DURABILITY		ACCURACY		SIZE		INTERFACING		SERVICING		POWER REQUIREMENTS			SIMPLICITY			RELIABILITY			EVA		
	8	9	9	9	10	8	8	8	7	7	7	10	10	10	7	7	7	10	10	10	7	7	7	10	10	10	7	7	7	TOTALS				
ASTEK SYSTEM	15	16	18	17	18	17	18	20	20	20	15	20	16	4	1526	**																		
JR3 SYSTEM	15	17	16	17	17	16	17	16	17	18	15	18	18	4	1470																			

\*\* Optimal Solution

# POSITION SENSORS

	DESIGN PARAMETERS				OPERATIONAL PERFORMANCE				DURABILITY				ACCURACY				SIZE				INTERFACING				SERVICING				POWER REQUIREMENTS				SIMPLICITY				RELIABILITY				EVA			
	8	9	9	9	10	8	8	8	7	7	7	10	10	10	10	10	10	7	7	7	10	10	10	10	10	10	7	7	7	10	10	10	10	10	7	7	TOTALS							
WEIGHT FACTORS	8	9	9	9	10	8	8	8	7	7	7	10	10	10	10	10	10	16	16	16	18	18	18	14	14	14	4	4	4	1260														
NEC SYSTEM	8	4	18	18	18	18	16	16	16	16	16	18	18	18	18	18	18	16	16	16	18	18	18	14	14	14	4	4	4	1260														
OPTICAL ENCODERS	14	16	18	18	20	16	16	16	10	10	10	8	14	14	14	14	14	10	10	10	8	8	8	14	14	14	4	4	4	1262 **														
LBJ SYSTEM	4	12	10	20	20	6	10	4	6	6	12	4	8	6	12	4	8	4	4	4	6	6	6	12	12	12	4	4	4	836														
POTENTIOMETERS	20	12	4	14	20	10	10	12	10	8	10	4	10	8	10	10	10	12	10	12	10	8	10	10	10	10	4	4	4	1046														

\*\* Optimal Solution

# PROXIMITY SENSORS

DESIGN PARAMETERS	EVA									
	WEIGHT FACTORS	8	9	9	10	8	8	7	7	TOTALS
COST	17	8	10	17	12	14	15	6	10	1051 **
OPERATIONAL PERFORMANCE	7	7	10	15	7	5	2	6	4	669
DURABILITY										
ACCURACY										
SIZE										
INTERFACING										
SERVICING										
POWER REQUIREMENTS										
SIMPLICITY										
RELIABILITY										

\*\* Optimal Solution

# TACTILE SENSORS

DESIGN PARAMETERS	EVA										TOTALS	
	COST	OPERATIONAL PERFORMANCE	DURABILITY	ACCURACY	SIZE	INTERFACING	SERVICING	POWER REQUIREMENT	SIMPLICITY	RELIABILITY		
WEIGHT FACTORS	8	9	9	10	8	8	7	7	10	10	7	1222
SANDIA SYSTEM	10	15	12	17	5	18	9	12	10	15	4	1249 **
SENSOFLEX	10	13	14	16	16	18	16	12	12	15	4	

## Optimal Solution

# SOLUTION OPTIMIZATION

## FRICTION BELTS

	SAFETY	BRAKING	SLIPPAGE	PRECISE MOVEMENT	VELOCITY	MULTI-SPEED	LOAD	MAINTAINABILITY	RELIABILITY	DURABILITY	STABILITY	REUNDANCY	SIZE	MASS	SIMPLICITY	COST	LACK OF EVA'S	HUMAN INTERFACE	ADAPTABILITY	SPACE STAT. DIST.	HOOK/UNHOOK PRODC.	POWER REQUIREMENTS	
WEIGHT FACTOR	10	9	9	10	7	6	7	7	8	8	8	10	5	7	5	4	10	5	9	10	10	8	TOTAL
TRI-FRICT. BELT	15	17	12	12	16	15	15	15	13	17	16	15	14	14	16	15	17	18	17	15	15	15	2602
BI-FRICT. BELT	15	16	12	13	16	15	15	16	12	15	16	16	15	15	17	17	17	18	17	15	15	16	2629
QUAD-FRICT. BELT	15	18	12	12	16	15	15	13	14	18	16	18	12	10	14	10	17	18	17	15	15	14	2567

SCALES: WEIGHT FACTOR 1-10, DESIGN CONSIDERATIONS 1-20

# SOLUTION OPTIMIZATION

## FRICTION WHEELS

WEIGHT FACTOR	10	10	5	9	9	10	7	6	7	5	7	7	8	8	9	8	5	10	10	4	8	10	TOTAL
DUAL	13	18	18	8	8	18	15	16	10	18	16	17	8	14	14	10	18	15	13	18	17	12	2356
TRI	12	16	18	10	9	15	15	16	11	16	12	14	9	15	12	8	17	14	11	16	16	13	2392
MULTI	14	14	18	12	10	15	15	16	12	13	8	12	13	17	14	11	14	15	12	10	12	18	2318
TRIAD	10	15	15	10	9	17	16	17	12	12	11	11	11	14	12	16	14	16	9	9	14	17	2248
IDLER/PULLEY	10	16	13	12	10	8	13	12	10	17	16	16	9	10	13	7	17	12	10	17	18	9	2077

SCALES: WEIGHT FACTOR 1-10, DESIGN CONSIDERATIONS 1-20

# SOLUTION OPTIMIZATION

## SPOOL TYPE

	SAFETY	BRAKING	SLIPPAGE	PRECISE MOVEMENT	VELOCITY	MULTI-SPEED	LOAD	MAINTAINABILITY	DURABILITY	STABILITY	REUNDANCY	SIZE	MASS	SIMPLICITY	COST	LACK OF EVA'S	HUMAN INTERFACE	ADAPTABILITY	SPACE STAT. DIST.	HOOK/UNHOOK PROC.	POWER REQUIREMENTS		
WEIGHT FACTOR	10	9	9	10	7	6	7	7	8	8	8	10	5	7	5	4	10	5	9	10	10	8	TOTAL
DUAL SPOOL MOND	6	12	9	7	16	12	17	11	12	17	13	9	10	15	4	11	17	2	3	6	15	1754	
DUAL SPOOL TRI	8	13	16	7	16	14	18	10	13	17	14	18	8	9	14	3	11	17	13	3	7	15	2052
WRAP AROUND	13	11	10	10	14	13	14	14	11	16	14	11	12	14	15	14	13	9	11	14	3	15	2082

SCALES: WEIGHT FACTOR 1-10, DESIGN CONSIDERATIONS 1-20

# SOLUTION OPTIMIZATION

## MISCELLANEDUS

	SAFETY	BRAKING	SLIPAGE	PRECISE MOVEMENT	VELOCITY	MULTI-SPEED	LOAD	MAINTAINABILITY	DURABILITY	STABILITY	REDUNDANCY	SIZE	MASS	SIMPLICITY	COST	LACK OF EVA'S	HUMAN INTERFACE	ADAPTABILITY	SPACE STAT. DIST.	HOOK/UNHOOK PROC.	POWER REQUIREMENTS		
WEIGHT FACTOR	10	9	9	10	7	6	7	7	8	8	8	10	5	7	5	4	10	5	9	10	10	8	TOTAL
ROBOTIC	11	16	11	8	7	2	14	10	11	13	11	7	12	14	12	8	15	14	10	10	10	12	1868
GAS	3	3	14	2	16	8	18	4	13	16	6	7	3	5	11	4	5	5	16	2	18	4	1439
ELECTROMAGNETIC	13	11	10	9	14	13	13	17	13	17	13	9	14	12	13	5	9	12	5	17	10	3	1957

SCALES: WEIGHT FACTOR 1-10, DESIGN CONSIDERATIONS 1-20



# SOLUTION OPTIMIZATION HOOK/UNHOOK SYSTEM GUIDES

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WEIGHT FACTOR	10	7	10	7	5	6	4	10	8	10	5	9	6	TOTAL
FOLDER	10	7	10	14	16	10	12	11	13	6	7	8	12	1120
CYLINDER	10	17	15	14	18	11	18	11	15	6	17	8	12	1224
FUNNEL	18	17	18	14	16	15	17	18	15	6	17	18	12	1504
ROLLER	15	19	18	13	16	15	16	10	15	13	17	17	12	1448
SPIRAL	12	15	12	12	17	7	16	8	5	4	17	4	4	905
SPOOL	18	15	15	15	13	17	16	16	15	15	15	17	17	1501

Matrix 3.5

# HOOK / UNHOOK MATRIX

DESIGN PARAMETERS	EASE OF OPERATION									
	SAFETY	COST	EVA/IVA REQUIRE	MAINTAINABILITY	RELIABILITY	SIMPLICITY	COMPATABILITY	POWER REQUIRE	SELF-RELIANT	TOTALS
WEIGHT FACTORS	10	7	10	8	8	7	6	6	5	10
ROTATING DISC	15	15	15	17	15	16	15	16	13	1184
SLIDE LOCK	17	15	13	15	16	17	13	17	14	1182
GATE CYLINDER	17	14	13	15	16	14	14	16	14	1034
DEAD BOLT	15	14	13	15	16	16	14	16	13	1143
LOCKING RING	14	15	13	15	12	14	13	16	12	1087

# DRIVE CONFIGURATION MATRIX

DESIGN PARAMETERS	SAFETY	COST	LIFESPAN	EVA / VA REQ.	MAINTAINABILITY	RELIABILITY	SIMPLICITY	SIZE	STABILITY	PRECISE MOVEMENT	EFFICIENCY	REDUNDANCY	TOTALS
WEIGHT FACTORS	10	7	5	10	8	8	7	5	6	9	7	8	
SINGLE	14	18	11	13	15	13	15	15	11	14	13	8	1202
DUAL	18	15	14	14	14	15	14	14	15	15	13	15	1331
DUAL/REGENERATIVE	19	13	14	14	14	15	11	13	17	15	16	16	1342

Matrix 3.7

# SLIDER BLOCK INTERFACE MATRIX

DESIGN PARAMETERS		SAFETY	COST	LIFESPAN	MAINTAINABILITY	RELIABILITY	SIMPLICITY	EFFICIENCY	TOTALS
WEIGHT FACTORS		8	7	5	10	9	7	7	
▶	ROLLER SURFACE	17	14	16	15	16	14	17	825
	SELF-LUBRICATING	18	17	15	15	17	19	18	900
		▼							

# BRAKING MATRIX

DESIGN PARAMETERS	WEIGHT FACTORS										TOTALS		
	SAFETY	COST	LIFESPAN	EVA/NA REQ.	MAINTAINABILITY	RELIABILITY	SIMPLICITY	SIZE	CONTROLLABILITY	EFFICIENCY	REDUNDANCY		
	10	7	5	10	9	9	7	6	9	8	8		
PULLEY ROTOR	16	13	16	14	16	17	15	16	18	17	12	1363	
PULLEY DRUM	15	12	16	13	14	16	14	15	17	16	11	1271	
ROTOR EXTENDED FROM PULLEY	19	13	16	15	16	17	15	15	18	18	14	1421	
DRUM EXTENDED FROM PULLEY	18	12	16	16	15	17	14	14	17	17	14	1375	
REAR SHAFT ROTOR	18	12	16	14	16	17	14	14	17	18	14	1372	
REAR SHAFT DRUM	17	11	16	14	14	16	16	13	16	17	14	1298	
COLD GAS JET	16	12	10	14	14	16	15	10	14	14	14	1219	
REVERSING MOTORS	16	15	17	15	15	13	14	19	12	14	14	1296	

SCALE:

WEIGHT FACTOR	INDIVIDUAL RATING
HIGH 10	20
LOW 1	1

	TECH. FEASIBILITY	REDUNDANCY	SAFETY	COST	RELIABILITY	EFFICIENCY	SIMPLICITY	DURABILITY	SIZE	TRANSPORTABILITY	AVAILABILITY	LIFE EXPECTANCY	DRAG EFFECTS	INTERFACE	MAINTENANCE	ENVIRONMENT EFF.	WATTS/KG OUTPUT	TOTAL
POWER SOURCE	9	9	10	7	10	7	6	9	10	9	10	7	6	8	8	8	7	
SOLAR ARRAYS	20	14	20	18	15	5	13	10	5	15	10	12	8	18	9	17	12	1875
RTG'S	20	18	12	13	20	10	15	20	12	18	18	16	20	19	18	12	14	2215
ELECTRO-DYNAMICS	5	13	18	19	18	17	20	12	20	20	20	16	5	12	18	18	20	2156

Matrix 4.1

# POWER SYSTEMS MATRIX

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## Matrix 4.2





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APPENDIX C

## PERFORMANCE PARAMETER DEFINITIONS

The following performance parameters were used in the Solution Matrices of Appendix B:

1. Accessibility - The ability to be approached or entered easily.
2. Accuracy - The ability to perform within a specific percentage of nominal.
3. Attenuation - Weakening of a data signal.
4. Availability - System's readiness to perform desired functions.
5. Braking - Essential to overcome gravity-gradient forces and to stop elevator motion.
6. CM Adjustment - Method by which elevator's center of mass is adjusted with respect to the tether.
7. Commonality - Ability to integrate with existing system.
8. Compatibility - The ability of interfacing with all other components.
9. Contamination Risk - The degree to which a component is vulnerable to contamination.
10. Controllability - Ability of a mechanism to maintain control of the elevator at any location on the tether.
11. Cost - Relative estimated price of the component.
12. Dexterity - Ability of a device to perform intricate tasks.
13. Disturbances - Disturbances that are induced on the Space Station as a result of elevator operation.
14. Drag Effects - Amount of drag induced on the Space Station by a proposed system.
15. Durability - The degree to which the elevator endures the space environment and wear undergone during normal operation.
16. Ease of Operation - The degree to which operation is made uncomplicated.
17. Efficiency - The ratio of the performance level of the device to the time and energy required.
18. Environmental Effects - Degree of the system's impact on the environment.
19. EVA/IVA - The level of external and internal activity associated with the operation the elevator.
20. External Storage - The ability to carry payloads externally without interference to elevator functions.
21. Feasibility - How realistic a particular design is in terms of engineering theories.
22. Flexibility - The ability of a device to do the wide variety of tasks required of it, presently or in the future.
23. Frequency Accomodations - Ability to provide high frequency transmissions.

24. Hook / Unhook - Procedure which includes all attachment and removal of the elevator from the tether.
25. Human Interface - Amount of crew involvement necessary for the operation of the elevator or its components.
26. Interference - Noise.
27. Internal Protection - The ability to protect internal components from the environment.
28. Librations - Complex vibrational modes induced by the elevator and transferred to the tether.
29. Life Span - Duration of time between implementation and replacement.
30. Load - The amount of mass that elevator is capable of pulling or dragging along tether.
31. Maintainability - The level of servicing required to keep the device in proper operating condition.
32. Mass - The quantity of matter.
33. Multi-Speed - Capability of drive mechanism to move at any speed between 0 and 5 m/s.
34. Payload Capacity - The total mass of the cargo which can be transported by the elevator.
35. Payload Interface - The junction between the elevator and its cargo.
36. Performance - A relative measure of how well the device carries out its intended function.
37. Power Requirement - Amount of power required for the elevator or its components to operate.
38. Precise Movement - Ability to move accurately to any location along tether.
39. Reaching Capability - Range of motion of a device.
40. Redundancy - Amount of auxiliary or backup units to insure operation in case of main unit failure.
41. Reliability - The number of failures per unit time.
42. Required Internal Volume - The amount of space required by the internal components or the amount provided by the elevator.
43. Robotics - All remotely manipulated devices which perform required activities on the tether.
44. Safety - The level of risk to the inhabitants and/or other components as a result of the operation of this device.
45. Self Reliant - Ability to operate free of external controls.
46. Servicing - Capability of a system to provide ease of repair.
47. Shielding - The proficiency at which the internal components are guarded or protected.
48. Simplicity - The relative ease with which the device can be fabricated, installed, and used.
49. Size - Ability to meet size requirements.
50. Slippage - Drive mechanism's inability to maintain precise contact with tether.

51. Software Adaptability - Relative ease in allowing for installation of computer software.
52. Stability - The degree to which the elevator maintains a prescribed orientation.
53. Stress Areas - Stress areas that occur due to sharp corners.
54. Technical Availability - The level of development that a system or a capability is at, or judged to be at, within the next five years.
55. Time - The amount of time required for the device to perform its required function.
56. Tool Interface - The degree to which tools interact with other components.
57. Transmission Rate - Amount and quantity of digital information which can be transferred from one point to another.
58. Transportability - The size of the elevator which affects how well it can be relocated.
59. Velocity - The speed at which the elevator is capable of traversing the tether.
60. Versatility - Ability to change or fluctuate readily.
61. Watts Output/Kg - Power output to mass ratio of the proposed system.
62. Worthiness - Proven success in space applications.

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